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FLIGHT TEST AND ANALYSIS PROCEDURES FOR NEW HANDLING CRITERIA

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SUMMARY

There is work underway to revise the US MIL-H-8501 and the UK Def-Stan 00970 design requirements for the specification of handling qualities for military rotorcraft. This paper reports on current RAE research activities in support of the two programmes. The focus of this work has been an extensive series of flight trials to investigate handling and performance requirements for low level nap-of-earth operations. The paper introduces and discusses results of trials on two different aircraft in a small amplitude, high gain pitch tracking task, and for two discrete moderate amplitude manoeuvres.

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1 INTRODUCTION

The ability of an aircraft to fulfill its intended role is critically influenced by the flying qualities bestowed upon it by the designers. Potential performance may be invested in a particular machine, for example in an agile combat helicopter, by virtue of such attributes as a large hover thrust margin, or high control power. However, a pilot can only tap this potential if the flight control system and associated handling qualities will allow him to do so. Hence, the specification of adequate design criteria as the yardstick that the designer will work to, is a cornerstone in the successful evolution of an aircraft from the drawing board to the achievement of full operational effectiveness.

In both the UK and the US, the mandatory requirements for the handling qualities design criteria of military rotorcraft have remained unchanged for the past 25 years or so. During this time rotorcraft technology has advanced considerably, including the advent of active control applications in helicopters and the prospect of tailored flying qualities and carefree manoeuvring. Moreover, the role of military helicopters has become increasingly diverse and demanding. For example, future battlefield helicopters will be expected to operate over hostile terrain in low level nap-of-earth flight, perhaps in difficult climatic conditions, or in air-to-air combat against other helicopters. Roles of this nature require precise and accurate flight path control and place high demands on both the pilot and on the vehicle's flight control system. In order to exploit the new technology in terms of an increased operational capability while maintaining acceptable levels of pilot workload, it is essential that the requirements specify handling and performance criteria that are appropriate to the intended role, and which identify the fundamental design features that characterise the desired dynamic responses. Hence, there has been a growing need to review and update the relevant documentation for design requirements, and recently there have been undertakings to this effect by the revision of the US MIL-H-8501 and the UK Def Stan 00970.

From a research perspective, it has been the concern of the Royal Aerospace Establishment, Bedford, UK, to conduct studies into handling and control in support of the development of active control for helicopters. Effort has been directed towards developing flight and simulation techniques, and mathematical modelling procedures, to enable the evaluation and prediction of the performance of different configurations. More specifically, attention has been focussed on investigating helicopter agility and pilot control strategy in low level flight (Ref 1, 2), and the way in which the vehicle's dynamic behaviour affects the level of task performance that can be achieved.

In addition to the specific research aims mentioned, the work has provided a basis for investigating suitable handling criteria for the specification of new types, and for specifying the desired level of agility (Ref 3, 4). Consequently, the opportunity has been taken to review the recommendations in the proposals and supporting reasearch activities for the MIL-H-8501 revision (Refs 5, 6, 7) and to evaluate some of the proposed test procedures and associated criteria. To create a suitable database, flight tests have been conducted with the RAE research Lynx and Puma, and this paper describes the tests and associated data analysis. The paper examines the merits of the proposed criteria and test procedures as a means of

specification and compliance demonstration for flying qualities. The paper is also concerned with the impact of handling and control requirements on the specification of agility requirements.

Particular areas of interest addressed include the requirements for both small and moderate amplitude manoeuvres, and results are presented for a high gain tracking task and for various discrete Mission Task Elements.

2 BACKGROUND

It is generally recognised that the nap-of-earth operational environment poses the greatest test of a helicopter's agility and flying qualities; the capability to enable precise and rapid changes in flight path, combined with good acceleration and deceleration capabilities are the prime requisites for flight in this regime. For conventional helicopters, linear acceleration is achieved through the re-direction of excess rotor thrust by means of attitude control, and hence requirements for roll/pitch control characteristics have tended to form a central feature of past and current design criteria. Typically, such criteria focus on the vehicles short and long term responses from the standpoint of damping or roll/pitch time constants, control sensitivity and control power considerations. Fig 1 gives an example for roll control and shows the criteria adopted for the present MIL-H-8501A and the criteria proposed in Ref 8 for agile combat helicopters. Other features that are usually addressed in performance specifications include requirements for maximum speeds in the fore and aft, lateral and vertical axes, together with requirements for angular rates and structural load factors. Although these aspects contribute towards establishing the maximum manoeuvre boundaries, there are no specific requirements regarding acceptable levels of agility within these limits. Indeed, the question of how to evaluate and specify the desired level of agility has been the subject of continuing investigations over the years.

Naturally, as the battlefield role for helicopters has evolved, the demand for greater agility has grown, and the trend has been towards building aircraft that are totally dedicated to nap-of-earth roles, eg LAH, LHX etc. With the increasing demands of the role in relation to weapons systems and threat avoidance etc, pilot workload has become a major issue in design studies for these new aircraft. The results from RAE's studies (Ref 3), and those from previous studies (Ref 9), provide clear evidence of the way in which handling and control constraints can cause increased levels of workload and prevent the pilot from using the full performance. This may be the case even in a machine regarded as having a high degree of inherent agility according to criteria such as shown in Fig. 1, eg hingeless rotor Lynx. The concern is, that while traditional handling criteria and peformance specifications may ensure potential performance, compliance with these criteria will not necessarily guarantee an adequate level of agility. On the other hand, the desired performance may be achievable, but only at the expense of considerable pilot compensation.

The problem has been addressed in several recent research studies, which have set out to establish suitable databases as a means of determining the definitive handling and performance characteristics for the agile combat helicopter of the future. In common with other studies elsewhere, RAE has developed clinical, role related flight tasks as a means of testing different aspects of an aircraft's flying qualities, throughout the flight envelope. This approach, based on well defined tasks coupled with a

requirement for accurate task performance, has become a widely adopted method of testing for handling qualities in both flight and simulation testing, for it is considered to offer the best opportunity for pilots to accurately identify a vehicle's handling characteristics. Flight tasks that RAE have evaluated, include discrete manoeuvres that require a mix of open and closed loop control strategies, and tasks of a continuous nature where a tighter closed loop strategy is more appropriate. In the first case, the tasks may represent typical repositioning manoeuvres in the low speed/hover flight regime. Here, the concern is the pilot's ability to make large, aggressive control inputs without undue handling problems, say for example, from the effects of cross-couplings, while maintaining an accurate task performance in holding height, plan position and heading deviation. The second case relates to precision tracking manoeuvres, where the pilot has to 'close the loop' around the task variables eg height, speed etc, a situation where potential Pilot-Induced Oscillations (PIO) problems may be exposed. Of course, in addition to handling and control aspects, other factors will act to influence the control strategy the pilot adopts, see for example those shown in Fig. 2. Hence, due consideration has been given to factors such as the task cues, task aggression and pilot workload.

Similar work in the US has culminated in the proposals for the MIL-H-8501 revision. One of the main features of the proposals is the inclusion of a comprehensive set of role related flight tests for demonstrating compliance with the various handling and performance criteria. Different specification formats, depending on the operational circumstances and the required *control response type*, eg rate command/attitude hold, attitude command/attitude hold etc, are systematically applied on a task-by-task basis for each control axis. The criteria address the performance aspects of attitude control, and they are applied on the basis of the amplitude of the attitude changes achieved in the given flight tests, ie small amplitude, moderate amplitude and large amplitude criteria. In each case, the Cooper-Harper rating scale, as shown in Table 1, is used to define the handling requirements, where Level 1 equates to scale points 1-3 and satisfactory performance, Level 2 equates to points 4-6 and an adequate level of performance and finally, Level 3 equates to points 7-8, which is the case where adequate performance is not achieved. Table 2 shows the Bedford scale for rating pilot workload as used in RAE's tests. The small amplitude criteria are relevant to and have been evaluated in the context of the continuous tracking tests that RAE have evaluated. To some extent, the moderate amplitude criteria are relevant to RAE's discrete manoeuvre tests, although in this case the approach adopted has generally conformed to the techniques proposed in Ref 6. Here, unified criteria are applied across the full manoeuvre envelope for each control axis. The following sections develop the concepts of the various criteria and discuss the analysis procedures pertinent to each case.

3 SMALL AMPLITUDE CRITERIA

In this section of the paper, we explore several aspects associated with handling criteria appropriate to small amplitude manoeuvring. RAE experience in the exploration of the pitch axis of primarily the Puma, but also Lynx, helicopters, Fig. 3, is used to illustrate the relevant issues. Topics of concern include the criteria themselves, flight test and analysis methods that are appropriate to the criteria, some results that we have obtained previously, and the analysis of inconsistencies

between actual pilot ratings of the aircraft and the ratings predicted by various forms of the proposed criteria. The research is being conducted to validate criteria that can be used in design, development and certification.

The bandwidth criteria that we have examined form one of the core elements of MIL-H-8501 revision Ref 5, and are to be used to assess handling qualities in small amplitude manoeuvres. The tracking phase of an air-to-air engagement, air-to-air refuelling or positioning over the stern of a frigate, for example, are small amplitude tasks that require precise and accurate control by the pilot. Such control can lead to Pilot-Induced Oscillation (PIO) if the pilot attempts to use the combination of vehicle dynamics and task demands to achieve high performance. Bandwidth criteria then, are appropriate for protecting against PIO by ensuring appropriate vehicle characteristics, but note that they do not explicitly incorporate details about the task characteristics. This is an important point for the appropriateness of the criteria, and one we will return to later. Fig. 4 shows two forms of bandwidth criteria proposed during the development of the 8501 revision, together with definitions of each parameter. Classical control theory tells us that open-loop system frequency response characteristics give an indication of closed-loop (and in our case the pilot closes the loop with a feedback gain) stability. The phase-limited bandwidth for example, is that frequency at which the attitude (pitch or roll) frequency response to pilot demand is 45° (in phase) less than the vehicle's attitude to demand crossover frequency of -180° - this margin is then a stability margin that should be familiar to control system designers. In the case of the application of this concept to handling criteria, the bandwidth is the frequency up to which the pilot can operate without suffering a loss in closed-loop performance as a consequence of operating closer and closer to the crossover frequency, at which point of course the pilot-vehicle system would tend to become unstable.

The other two parameters are the phase delay and the phase slope, defined as shown. It is assumed that they give some indication of the rate at which the pilot encroaches on the region of potential PIO, or how rapidly he will pass through the crossover frequency and tend to drive the combined pilot-vehicle system unstable. When combined with bandwidth, it is postulated that these parameters characterise particular levels of handling qualities in small amplitude tasks, and this is reflected on the diagrams by boundaries that delimit Level 1 (satisfactory), Level 2 (acceptable) or Level 3 (unacceptable) handling qualities. The questions we have sought to address in our study of these important criteria concern whether they are appropriate, correct and complete.

3.1 Testing for compliance demonstration

Frequency sweep inputs and time series analysis methods are the means of demonstrating compliance with the criteria, suggested in the 8501 revision. RAE experience with frequency sweeping reflects that presented elsewhere, such as the widely published work of Tischler (Ref 10), in being very positive. Unlike the use of multi-step inputs for identification of aircraft dynamics, where extreme attitudes and changes in flight path may be achieved, the sweeps can generally be adjusted to produce small perturbations in attitude and flight path about the trim condition. The exact shape of the input is not crucial to the analysis, particularly if data is averaged over several runs. The test pilot is coached by the flight observer who counts out timings for 24, 20, 16, 12, 8 and 4s to aid him

For higher frequencies, observer counting can disrupt the considerable level of concentration required. It has been found that this approach allows the use of only single runs of about 120s in length in the analysis, and still gives excellent results (good input-output coherence). With the Puma, it has been found that of all control inputs, sweeps involving longitudinal cyclic are the easiest to fly, with pedal inputs being the most difficult. Part of the analysis at RAE involves taking the aircraft characterisation for bandwidth a stage further than suggested in Ref 5, by calculating an equivalent system parameter set for the aircraft. This requires a dissimilar verification input, eg a doublet. Although a broad database of Puma response to multi-step inputs has been collected at RAE, it has become standard practice to complete each sweep with a doublet to provide data directly relevant to the vehicle configuration and test conditions for the frequency sweep.

A few, but nonetheless significant, negative aspects associated with the use of frequency sweeps are worthwhile to highlight. Firstly, any aspect of a given configuration's response characteristics such as cross-coupling or the presence of instability that manifest themselves to any noticeable extent, can degrade the quality of the sweep itself and the validity of any single-input, single-output analysis. Immediately, it can be seen that unaugmented helicopters in general will be difficult to test. Instability can render sweeps impossible to perform; unaugmented, the Puma is only marginally stable and this can be seen to affect the quality of the longitudinal cyclic sweep shown in Fig. 5. In level flight below 120 kn, the Puma's marginal stability is a phugoid-type of low frequency. As can be seen, sweeps in such conditions tend to miss out these low frequencies, although in general this may not be of too great a concern since the crossover frequency will be somewhat above that for which the pilot has to apply compensation for instabilities. In Fig. 6, where the sweep has been performed with autostabiliser engaged, the data has a much higher and more easily visible low frequency content. Secondly, the effect of cross-coupling is mainly to give rise to off-axis control inputs, not in itself a great restriction except that it requires analysis tools that can perform multi- as opposed to single-input analysis. Although the magnitude of the cross-coupling may not be significant enough to result in excessive changes in attitude and flight path, natural piloting technique is to apply compensation for cross-coupling. It is difficult, in general, for the test pilot to untrain himself in this respect; Fig. 5 shows that for sweeps of the longitudinal cyclic with the unaugmented aircraft, where there is considerable pitch-to-roll coupling, there is apparently an insignificant amount of correlated compensation. However, the control time histories during a pedal sweep indicate significant levels of activity in all controls except collective, Fig. 7. The natural tendency in this instance is to compensate, to a considerable extent, for the strong pitching and rolling that pedal activity induces. Note that no analysis has been attempted using this data - it has been included simply to highlight potential difficulties in relation to single-input, single-output analysis of a conventional unaugmented helicopter. Finallv, considerable fatigue damage can be inflicted on the airframe particularly during a pilot's early exposure to this technique. The nature of this concern is shown in Fig. 8, which compares cyclic and load factor activity during two sweeps, one flown by a pilot experienced with the technique, the other with a pilot who was not. The latter demonstrates a common trait we have found with pilots new to the technique, and that is to increase input

amplitude with increasing frequency. The comprehensive instrumentation fit of our Puma, a software-based lifing system and manufacturer guidance, has allowed any damage to be quantified for major airframe components. Additionally, it is suggested that real-time telemetry be used to monitor airworthiness, since our experience is that a full understanding or knowledge of high frequency modes or resonances may not be available.

3.2 Analysis for compliance demonstration

Analysis of the frequency sweep data is split into two parts; firstly, time series analysis methods are used to derive the pitch rate to longitudinal cyclic frequency responses, from which phase delay, phase slope and bandwidth can all be measured graphically. Secondly, an equivalent system model, in this case in classical short period form, is derived from the frequency responses. This second stage is not part of the process of compliance demonstration given in MIL-H-8501 revision, but it is one carried out at RAE as a matter of routine. The pros and cons of doing so are discussed more fully later, but basically the equivalent system can give all the information necessary to demonstrate compliance, as well as providing the basis for greater insight into the validity of the frequency response. The short-period type pitch axis dynamics have been characterised for speeds between 60 and 120 kn with the augmentation system both engaged and disengaged. In addition, models have been derived for 60 kn augmentation on, and with full forward and full aft cg. The nominal mass for all work was 5500 kg. The model structure used to characterise the Puma was of conventional form, viz

$$\begin{bmatrix} \dot{\alpha} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} Z_\alpha & Z_q \\ M_\alpha & M_q \end{bmatrix} \begin{bmatrix} \alpha \\ q \end{bmatrix} + \begin{bmatrix} Z_{\eta 1s} \\ M_{\eta 1s} \end{bmatrix} \eta_{1s} \qquad (1)$$

with added time delay in incidence and pitch rate to capture high frequency phase effects ('phase roll-off') due to the actuation and rotor dynamics. In transfer function form, equation (1) becomes

$$\frac{\alpha}{\eta_{1s}} = Z_{\eta 1s} \frac{s - \delta_\alpha}{s^2 + 2\zeta\omega_n s + \omega_n^2} e^{-\tau_\alpha s} \qquad (2)$$

$$\frac{q}{\eta_{1s}} = M_{\eta 1s} \frac{s - \delta_q}{s^2 + 2\zeta\omega_n s + \omega_n^2} e^{-\tau_q s}$$

It is pertinent to emphasise that these delays are truly equivalent or effective delays, since the aircraft possesses no digital elements in the flight control system. The delay term is simply an artefact that captures high frequency lag or non-minimum phase dynamics. Note that the phase delay is a different parameter from this pure time delay, but for certain dynamics (and this is approximately true of the Puma) they can have similar values; in the case of the Puma they differ by about 30 ms. It is approximately the case therefore that phase delay and time delay can be used interchangeably.

Fig. 9 shows the pitch rate to longitudinal cyclic frequency response, together with equivalent system match, derived from one of the sweeps shown earlier. This is representative of the quality of fit that is achieved for modelling the Puma in pitch in forward flight. Phase slope, phase delay, equivalent time delay and both gain- and phase-limited bandwidth for each of these configurations are shown on Fig. 10. A broad range of these handling qualities parameters has been achieved by varying configuration and flight condition. The aircraft's dynamic characteristics across the range of test points are perhaps best summarised by Fig. 11 which shows the equivalent system parameter values. The dominant effect of the augmentation system is to nearly double the short-period natural frequency across the speed range, and to substantially reduce the damping ratio. The aircraft has a strong trend to manoeuvre instability above 100 kn with the augmentation disengaged, as can be seen by the decrease in natural frequency above 100 kn. This feature of the Puma's response is very noticeable to pilots of this aircraft, and has featured prominently in the comments of all participating aircrew. The pitching moment per unit control term indicates that while the aircraft has only moderate control sensitivity, it is certainly not lacking and it does increase with increasing speed. For example 0.040 rad/s^2/% corresponds in terms of stick movement, to 0.314 rads/s^2/in. The Lynx, with control power rated as high by pilots, has a corresponding figure of 0.628 rad/s^2/in. The Puma's control power featured strongly in pilot comments returned after the handling experiments, but this was related to the rather high equivalent delay, the effect of which was to, at least initially, give the impression, of poor control power. The equivalent time delay in the pitch rate response, is around a substantial 200 ms. Approximately 100 ms is due to the actuation system, the rest from higher order rotor dynamic effects.

3.3 Handling qualities results

Four test pilots took part in the handling qualities evaluation, and their individual experience and backgrounds are summarised in Table 3. The handling evaluations were based on a 'head-down' tracking task, requiring pilots to track, using the attitude indicator, attitude cues called by the flight test observer. The cues have been designed so that their mean is approximately zero, and that the aircraft does not stray too far from the trim condition, with attitude excursions limited to ±10°. The cues are not strictly random in nature, having been selected at 3 s intervals from a time history constructed from a sum of five equi-amplitude sine waves of varying frequency. This task has satisfied the need for a technique that exercises the pitch axis response characteristics in such a way that the resulting data can be used in an assessment of bandwidth criteria. Although artificial, the task can be designed to produce piloting control strategy that exposes latent PIO tendencies, Ref 11. The longitudinal cyclic control input, pitch rate, pitch attitude and airspeed perturbations are shown in Fig 12, from one run flown by P1 at 80 kn with augmentation engaged. Note that for a task that requires peak attitude perturbations

of 7.5°, the pitch rates and attitudes achieved are as high as 20°/s and 10° respectively, testifying to the task aggressiveness and to some extent the inherent vehicle deficiencies in relation to this task. The pitch attitude time history in particular clearly shows the perceived overshoot characteristics that all the pilots complained of, which gave rise to a degradation in perceived task performance. The control input autospectrum for this run is shown in Fig. 13. Note that power levels only start to diminish appreciably above about 0.8 Hz (5 rad/s), although the dominant task frequency is only 0.33 Hz (2.1 rad/s). The control strategies applied by the other pilots for the same configuration are compared in Fig. 14, and it can be seen that they are all similar. These results highlight that the task is consistent and repeatable (from the point of view of applied control strategy), and that the pilot is exercising control aggressively enough to command inputs at a fairly high frequency, which is necessary if latent PIO tendencies are to be exposed.

The derived models of the Puma were used to characterise the aircraft in terms of phase delay, time delay and phase slope versus bandwidth forms. Both phase- and gain-limited bandwidth are examined, but we shall concentrate firstly on phase-limited bandwidth (this is in accordance with the guidance given in Ref 5 for attitude response types, which the Puma's pitch response can best be characterised as). For now, we will also use the form of the diagram as shown in Fig. 4. Fig. 15 shows the location of each configuration tested (except 100 and 120 kn unaugmented) on the delay (remember in the case of the Puma this can approximately be either phase delay or time delay) bandwidth diagram, and Fig. 16 shows the same result but with each location annotated with the averaged (taken over the four pilots) pilots ratings returned using the Cooper-Harper (Ref 12) scale. The average rating in this case is used simply because it is a convenient statistical measure of the overall rating of the aircraft. The 100 and 120 kn unaugmented configurations are not represented on these figures because their projected bandwidth lies in that low frequency area of modelling where confidence in the linearity of the derived model (indicated by the coherence function) is very low. Note from Fig. 16 that the locations of both the augmented and unaugmented configurations on the diagram display only some correlation with the handling qualities ratings, which have been returned for the pitch axis only. Particular anomalies of note include 120 kn with augmentation engaged, 60 kn augmentation engaged but with aft cg, and the two unaugmented configurations, whose rating is not nearly so poor as that predicted by their location on the diagram. To explore further the relationship between the pilot rating and the bandwidth, Fig. 17 shows the average pilot ratings (with upper and lower bounds defined by the corresponding standard deviation) plotted against bandwidth. Note that overall, the trend is for the ratings to increase as the bandwidth decreases (as might be expected), although there is a relatively broad flat spot between 1.5 and 2.5 rad/s over which the ratings are approximately constant. The equivalent delays for these five configurations are also given on Fig. 17, but both the magnitude by which they vary and their lack of any trend with decreasing bandwidth, fails to explain the flat spot in pilot rating. The indication is therefore, that for the region of the delay-bandwidth diagram within which the augmented Puma lies, the handling qualities ratings are not as sensitive to a variation in bandwidth of 1 rad/s as the relative locations of the Level 1 and Level 2 boundaries would tend to suggest. An additional intriguing result is presented in Figs. 18 and 19, which show, by way of comparison with Figs. 15 and 16, a characterisation of the Puma in terms of gain-limited bandwidth. These results show greater correlation between aircraft location on the

diagram and the averaged pilot ratings. This includes the 100 and 120 kn unaugmented configurations, which now appear on the diagram. Only the 60 kn configuration with forward cg has a location that does not correlate with the pilot rating. Otherwise, the extent by which the aircraft locations vary with speed correlates with the ratings. The relevance of gain-limited bandwidth for the Puma is returned to soon, but it ought to be inappropriate, given the guidance proposed in Ref 5. Firstly, the aircraft response is more akin to that of attitude rather than rate type, and in such cases, phase-limited bandwidth is specified. Secondly, given the circumstances of a choice between gain- and phase-limited bandwidth, the lower should be chosen - in the case of the Puma, phase limited bandwidth is in general the lower.

An example of the identification of pilot control strategy, used to resolve the inconsistencies outlined above, is shown in Fig. 20. The comparison between the pitch rate to longitudinal cyclic model of the Puma identified from the frequency sweep (open-loop) data, with the pitch rate to cyclic model obtained from the tracking (closed-loop) experiment, is for the 80 kn, augmentation engaged configuration. It is clear up to which frequencies the pilot "modifies" the vehicle dynamics as a consequence of the task. This 'peak pilot operating frequency' has been obtained for each pilot-configuration combination, and used to calculate effective gain and phase margins to which each pilot operates. The two configurations with forward and aft cg are excluded from this part of the analysis, because their rating is directly influenced by their respective difference in time (phase) delay, as revealed by the pilots' comments. For all the other configurations, the averaged pilot ratings with standard deviation bounds, are plotted against the effective phase and gain margins respectively, shown in Figs. 21 and 22. Fig. 21 shows that the pilot rating trend becomes asymptotic to a value of just below four above effective phase margins of about 30°. For gain, no such obvious well-defined trend is apparent as the spread of points is concentrated in a very small range, and several of the points appear in a group that has a very small variation in effective margin, but a large variation in pilot rating (3.6 to 6). This result could indicate that for the configurations tested, the pilots operated to phase rather than gain margins in the region of incipient PIO. The fact that the asymptote on Fig. 21 lies just outside Level 1, even up to phase margins approaching 45°, is most probably due to the high value of equivalent delay (around 200 ms) inherent in all these configurations. Pilot comments are dominated by references to the degrading effect that effective delay has on the handling qualities, and indicate that it makes a significant contribution to the decision not to rate the aircraft as Level 1.

With all the mid cg configurations, the pilots commented simply on the degrading effect of the substantial delay present, and not on its changes with speed or augmentation. The greatest difference in delay for all these configurations is 30 ms. The forward and aft cg configurations were specifically examined together to quantify the effects of changes in the equivalent delay. Only test pilots P1 and P3 were involved in this part of the experiment, and a speed of 60 kn with augmentation engaged was chosen because it provides the highest bandwidth of all the test points, which should obviate any degrading effect that poor bandwidth may have on the handling qualities. Given the fact that only two pilots briefly assessed these configurations, the results cannot be regarded as definitive. However, the comments of both pilots in relation to the changes in delay effect between both configurations, feature very strongly in their

assessments, and this is in fact reflected in the pilot ratings. Both pilots reported that the aft cg configuration delay effect, while noticeable, was nowhere near as intrusive as that for the forwards loaded configuration, and both pilots accordingly gave the former one Cooper-Harper point better than the latter. The difference in effective delay between both configurations is 50 ms, and the tentative conclusion is that, like the fixed-wing experience, 50 ms of delay will tend to degrade handling qualities by one Cooper-Harper point. Note that on this basis, the level of the asymptote in Fig. 21 is consistent with the amount of equivalent delay present.

The phase-limited bandwidth for all ten configurations flown was recalculated using the margin of 30° suggested by Fig 21, 30° being the point at which the curve indicates that decreasing bandwidth will begin to degrade handling qualities. The new location of each configuration on the delay-bandwidth diagram is shown in Fig 23, with the Level 1-2 boundary tentatively redrawn to be consistent with the results presented above. To fix the location of any boundary, it would be necessary to have a sequence of points through which the line could be drawn. The nature of the boundary as drawn must be inferred from the available data, backed-up by pilots' comments. All of the six augmented configurations flown (with the exception of 60 kn aft-loaded) are rated at best marginally as Level 2, with pilots continually referring to delay effects as being intrusive and contributing substantially to the degredation in handling from Level 1 to marginal Level 1-2. The Level 1 boundary is accordingly 'bent over' to limit Level 1 handling qualities to an area below time delays of 200 ms. The exact shape of the curve is not however fixed by the one point firmly rated as Level 1 (60 kn augmented, aft-loaded) which now appears to be the only inconsistent test point. The augmented configurations in addition now lie (with the Level 1 boundary 'bent over') in an area of the diagram where a broad range of bandwidth (about 1-4 rather than 1-2 rad/s) is in the Level 2 area. This area of the diagram and the corresponding pilot ratings now correlate with the results presented earlier, where the ratings are not as sensitive to a change in bandwidth of 1 rad/s as the boundaries proposed in Fig. 4 suggest. The pilot ratings returned for the unaugmented configurations, principally because of the use of a 30° stability margin in phase, now show greater correlation with the Puma's location on the delay-bandwidth diagram.

Before continuing with our presentation of moderate amplitude manoeuvre criteria, it is pertinent to consider our results above in terms of two other forms of bandwidth criteria - phase slope-bandwidth, and the latest version of phase delay-bandwidth in the MIL-H-8501 revision, Ref 5. The former had a fairly short lifespan in the history of the development of the revision to MIL-H-8501, being superseded by the latter. It was originally proposed to obviate potential difficulties in the conduct and analysis of open-loop (frequency sweep) testing for compliance demonstration. Experience with Bell 214-ST data (Ref 13), tended to suggest that testing to the frequencies required for graphical measurement of phase delay from frequency responses, could be impractical. This was because it requires data up to twice the crossover frequency, which has potential for exciting lightly damped rotor modes which could 'contaminate' the response in the frequency range of interest. In any case, it may be impossible to get high frequency data due to flight safety considerations. It can be visualised that phase slope could be an important handling qualities parameter, since it describes how quickly the closed-loop pilot-vehicle system goes unstable as pilot gain increases. Fig. 24 shows the Puma characterised in terms

of phase-limited bandwidth, and phase slope, together with the averaged pilot ratings returned from the tracking task. Once again the 100 and 120 kn unaugmented configurations do not appear on the diagram. It can be seen that the data provided by the Puma experiments does not substantiate these boundaries, and exploration of the inadequacies will indicate that this particular criterion is both inappropriate and incorrect for the Puma data. The unaugmented aircraft, for example, is more severely rated on this diagram than by the pilots, while the spread in location and levels of flying qualities predicted for the augmented configurations does not correlate with the pilot ratings. Use of the 30° phase margin would improve the correctness of the criteria in the case of the unaugmented Puma results, but considerably worsen it for the augmented aircraft, since these latter points would all be driven more deeply into the Level 1 area. This is despite the fact that the pilots were adamant that the aircraft is a Level 2 machine. Further investigation of the variation in pilot rating with phase slope, Fig. 25, tends to substantiate the premise inferred by Fig. 24, that the flying qualities are almost independent of phase slope over a broad range of values of this parameter. Note that the two unaugmented configurations are more poorly rated because of low bandwidth, and the single configuration in the Level 1 zone is better rated because the effective delay is perceived to be much less intrusive. The configurations with similar pilot ratings but widely varying phase slopes are the same as those in Fig. 17 with a range in bandwidth of over 1 rad/s - the flat spot in vehicle rating cannot be explained by decreasing phase slope. The inappropriateness of phase slope as a handling qualities parameter is further emphasised by the consistency among pilot opinion that perceived delay is very intrusive and affects pilot delay accordingly - this does not seem to be the case with phase slope. Finally, Fig. 26 shows our data in terms of a criterion recently proposed (Ref 5) for air combat. Movement of the boundaries is the difference between this diagram and the original one on Fig. 4, and it is apparent that the augmented configurations are inconsistent with the criterion, and rates our unaugmented configurations much more severely than the pilots did. The limited amount of data from the Lynx experiments is also shown on this diagram - pilot opinion of the Lynx in the tracking tasks was not as rigourously sought as in the case of the Puma experiments, but it was generally noted that the aircraft is Level 1. Note that satisfying Level 1 handling qualities in air combat will be difficult - the Lynx, with its semi-rigid rotor system falls outside the Level 1 boundary. Further, the phase delay (and incidentally pure time delay) is around 150 ms - addition of a digital fly-by-wire system, without attendant improvements in bandwidth, is quite likely to move the aircraft vertically up the diagram and deeper into the Level 2 region. However, a substantial contributor to the phase delay is the actuation system dynamics, contributing about 80 ms, and in any case any high-bandwidth FBW system is likely to need faster actuation than this. Given that a semi-rigid rotor aircraft barely meets Level 1 it will be interesting to see if articulated (or bearingless equivalents) can meet the Level 1 criterion, with or without augmentation - indeed, what augmentation will be required. It is interesting to note that use of a 30° phase margin would move all these points to the right, and render this criterion, with these boundaries, more correct in terms of pilot assessment of both Puma and Lynx.

3.4 Discussion

Our results in the area of bandwidth criteria suggest that they are appropriate as a small amplitude criteria; of all the forms examined, only one is correct, and even then only with modification. These results must

be kept in perspective, since in the main, they are limited in scope to only four pilots and one vehicle type, although this one type does offer a broad range of handling qualities parameters. Accordingly, although a definitive statement on the appropriateness of bandwidth criteria cannot be made without a much more substantial database, it is felt that the analysis performed does provide a rational and consistent basis that can be used to justify the modifications that have been suggested. Certainly, the anomalies and ambiguity resulting when the suggested criteria are applied have been resolved, through the non-parametric identification of pilot control strategy backed up by pilot comment, the latter is regarded as essential to exploit the data fully and correctly. The results do however offer a contribution to the available handling qualities database, but there is some detail associated with the analysis of the data that we have not yet discussed, but which is of relevance to development of the criteria and the validity of our conclusions. The use of more mature forms of the criteria for design guidance or compliance demonstration also need consideration.

Firstly, we have several longitudinal cyclic frequency sweeps of varying amplitude, but at nominally the same flight condition which we can use to assess the impact of input size on the handling qualities parameters. This is of concern because of the apparently differing input amplitudes in the open-loop tests shown in Figs. 5 and 6, and the closed-loop test shown in Fig. 12 - one could question the relevance of the dynamics characterised by the sweep with those flown during the tracking experiment. Fig 8 shows two sweeps, at nominally the same flight condition. In one the input is around 3-4 times larger than the other in the higher (bandwidth) frequency region. The handling qualities parameters derived from both, are however very similar - the biggest difference in handling qualities parameters is in phase limited bandwidth, one sweep suggesting 1.76, the other 2.05 rad/s. It may not be the case for rotorcraft in general, but this Puma result does tend to suggest that the handling parameters are relatively insensitive to frequency sweep amplitude.

A similar question to that of the linearity of response with input amplitude, concerns the effect of the augmentation and control system, principally whether or not it has been saturated, either through authority limits, or actuation rate limits being exceeded. If the former effect was present to any significant extent, it could explain why there is a relatively small spread of handling qualities ratings across the speed, loading and augmentation configurations tested. The autopilot gains and authority limits are known, and combined with the perturbations experienced during the tracking experiments indicate that the authority limits were close to being exceeded (but were not) at only two points during the tracking run. The pilots therefore indeed benefited from the bandwidth improvements offered by the augmentation system. Of more concern, is the possibility of exceedence of the actuation system rate limits, but analysis suggests that they were not exceeded during the run.

The task we have proposed (pitch tracking) would seem to have all the attributes necessary for examining bandwidth, and as we have said earlier, a good task is essential if one is to explore bandwidth adequately. Choice of a task with very low task bandwidth, is quite likely to return Level 1 ratings of the aircraft, but of course it is a rating of the aircraft in relation to that task. Another task that required an inherently higher frequency of pilot inputs and/or more aggression in such circumstances could elicit worse than Level 1 ratings. This is a concern not of the

designer who has to demonstrate compliance with a mature specification, but for the researcher who has to assess appropriateness, completeness and correctness. Our task can of course be criticised as it is not a mission task element. However, it is taken to be representative of the tracking phase of an air-to-air engagement, and it is similar to that used by other experimenters, especially Heffley (Ref 6). We are however aware of two potential difficulties with the task that could have a strong impact on the analysis and results themselves; these are learning effects (ie did the pilots learn the cues so that they could anticipate the demands), and the fact that the cues could be called in such a manner that pilots could not stabilise on a commanded attitude, and not really tightly maintain the commanded attitude. Although we really have to rely on pilot comment to address these points, there is some evidence that serves to relax this concern. Both the project pilot (P1) and pilot P4 (who was the most experienced on type) spent a considerable effort tuning the task so that it was demanding enough while not being such that it forced pilots to discard stabilising on the attitudes. Pilots commented that the task was demanding and could not be learned so that the cues could be "pre-empted", and at only two cues in the task could they not stabilise on a demanded attitude because of an inability to get a rapid enough initial response. If in general during the task, the pilots made no attempt to maintain tightly the commanded attitude (indeed in the limit simply made step inputs proportional to the magnitude of the cue), then the consequence would be that almost all input power would be applied in the region of the task bandwidth, and the pilot-in-the-loop characteristics would not differ from those of the basic aircraft. Fig. 14 indicates that the input power is fairly evenly distributed up to about 1 Hz, with a peak at a frequency slightly higher than that of the dominant task frequency. Additionally, Fig. 20 shows that, up to a fairly high frequency (somewhat higher than the task bandwidth), the pilot-in-the-loop characteristics are significantly different from those of the basic Puma. These results provide the objective support for the pilots' assertion that they could not 'learn' the task, and that they were exercising 'tight' closed-loop control.

The final topic of discussion concerns the use of equivalent systems, and the associated consideration of phase delay versus pure time delay as handling qualities parameters. Phase delay and phase slope are parameters that can like bandwidth be measured graphically, - for the dynamics of rotorcraft in general, the same is not true of pure time delay which needs to be extracted by the equivalent systems approach. In our work, the results (pilot comment) give compelling evidence for adopting pure (effective) time delay - it has manifested itself very clearly to our four pilots, and as a consequence, by virtue of its relatively high value with the Puma, has directly affected the rating of the aircraft, particularly the decision not to rate it as Level 1. We accept, however, the difficulty associated with use of such a parameter in a specification that is to be rugged, robust and easy to use for compliance demonstration. It requires an appropriate model structure, and criteria for mismatch between the full and low order systems. In general however, we feel that the door should not be closed completely on this approach, or the adoption of pure time delay as a handling qualities parameter because of the potential benefits. For example, an additional benefit of an equivalent systems approach is that the resulting model can be driven with verification inputs of varying amplitude and frequency to safely (and cheaply) establish the appropriateness of the frequency response originally derived from the sweep input, as a characterisation of the aircraft. The rapidly expanding knowledge and

experience base in rotorcraft system identification should serve well in establishing an appropriate way forward if the equivalent systems approach is adopted in future.

4 MODERATE AMPLITUDE CRITERIA

In manoeuvring flight, a helicopter's handling and performance capabilities are to a large degree governed by the angular motion characteristics and hence the Ref 5 proposals for the MIL-H-8501 revision uses the aircraft's short, mid and long term attitude responses as the basis for defining the various amplitude criteria. For small amplitude manoeuvres, ie attitudes below 10°, the response is dominated by the vehicle's open loop bandwidth characteristics, and as described in the previous section, the bandwidth forms the basis for criteria in this category. For large amplitude manoeuvres, ie attitudes in excess of 40°, the control power or peak rate at full control is the dominant factor governing the response, and so here the criteria are couched in terms of a minimum peak rate requirement for each axis. For moderate amplitude manoeuvres, ie attitudes of between 10° to 40° both bandwidth and control power will influence the attitude response, and in this case the criteria (see also Ref 6) are represented by a flying qualities parameter, based on the ratio of peak angular rates and associated attitude changes. Expressed in this form, the criteria are essentially performance oriented and they are formulated on the premise that if all the conditions are met, ie requirements for each control axis plus cross-coupling effects and engine response etc, then the aircraft will return Level 1 handling qualities.

To assess the vehicle's overall handling capabilities, Ref 5 introduces a number of role related Mission Task Elements (MTEs). RAE has adopted similar test techniques for its own research into helicopter handling and performance, although in this case the main objective was to establish suitable means of evaluating a helicopter's agility, and to determine the influence of factors such as the handling qualities, task cues, pilot workload and task aggression on the level of performance achieved. The main consideration in devising suitable tasks was that the tests should be truly representative of the nap-of-earth operational environment, while giving the pilot sufficient scope for exercising the aircraft's full performance. Studies of the standard tactics adopted for battlefield helicopters show that typical combat missions consist of high speed runs to and from the battlefield, while making use of available ground cover to avoid detection, and a low speed phase for execution of tasks such as target acquisition, weapon aiming etc. In both cases, discrete manoeuvre elements, or mission task elements in the parlance of Ref 5 can be identified; for example turning and climbing manoeuvres to avoid obstacles, sidestep and bob-up/down manoeuvres from/to cover, or quick starts and stops to re-locate the aircraft. Such manoeuvres are essentially discrete tasks consisting of a series of discrete attitude changes to achieve the desired change in flight path. The modelling of discrete manoeuvring tasks forms the basis of the moderate amplitude criteria proposed in Ref 9 and discussed further in Ref 6. RAE has used results from its tests to evaluate both sets of criteria for a wide range of cases in either hovering, climbing, turning and forward flight. For brevity this paper is constrained to results for two cases in the hover/low speed regime representing the fore and aft and lateral control axes.

Agility criteria in the Ref 5 proposals are expressed in terms of a maximum requirement on the time taken to achieve the maximum linear accelerations and decelerations. There is also a minimum requirement for the normal load factor in turning flight, which will act to set the performance standard for the achievable rate of turn. RAE has adopted a more direct approach to the problem of agility specifications by developing specific agility metrics, based on the manoeuvre kinematics, ie acceleration velocity, distance and time, for setting the desired level of performance. One of the main considerations has been the need to determine criteria that adequately reflect the demands of the intended role, and that are sensitive to the net effects of the vehicle's flying qualities. To this end RAE has proposed an agility factor, based on the ratio of an ideal task performance to the actual performance achieved in terms of the time taken to complete the task. Factors such as the level of thrust available, engine and rotor governing and attitude control will act to determine the level of agility by setting the magnitude and rapidity of the acceleration response. Flight experiments have demonstrated that the agility factor is not only sensitive to the effects of acceleration transients, but also to the net level of handling qualities achieved. Hence, for a given task, a specification based on a given agility factor and level of handling qualities will serve to set, for example, the engine power and response requirements and the attitude response characteristics. The agility factor was first introduced in Ref 1 as a measure of a helicopter's turning performance in a hard turn manoeuvre, together with a measure of the effective radius of turn, over a range of speeds. Since then the idea has been developed and applied to a range of different manoeuvres. The following sections discuss the concept in greater detail.

4.1 Angular response characteristics

In practice, the attitude dynamics achieved in performing a typical discrete manoeuvre, such as the lateral sidestep mission task element, can be summarised as shown in Fig. 27. The rate (P) and attitude (ϕ) time histories, and the associated phase plane plot, clearly show the roll attitude and rate peaks commanded by the pilot at the acceleration, reversal and deceleration stages of the manoeuvre. The rate peaks reflect the degree of pilot aggression in commanding the desired response, and the ratio of maximum peak rate to the attendant change in angle of bank ($\Delta\phi$) provides a convenient means for summarising the maximum manoeuvre demands. Using the full range of MTE's, the ratios achieved can be used to map the envelope of manoeuvre demands for the roll axis for a range of different amplitude manoeuvres. The ratio of peak rate to net attitude change is used as a basis for specifying a performance requirement for attitude control in each axis; Fig. 28 gives examples for roll and and pitch control. To demonstrate compliance with these requirements, control step or pulse input tests are necessary, involving attitude changes from one steady attitude to another, using attitude changes representative of those achieved in the MTEs. The boundary lines represent minimum requirements at different levels of 'acceptability' for the performance achieved, at maximum pilot aggression, and the Level 1 boundary represents the minimum requirement for compliance with the criteria. Under certain failure modes and operating conditions, the requirement is relaxed to the Level 2. In terms of design features, the importance of such criteria is that they act to set a requirement for parameters such as the rotor stiffness, control gearing etc and the actuator performance.

An alternative approach, based on the same performance criteria, is suggested in Ref 6. The proposed formats, again using roll control as

the example, are given in Fig. 29. In this case it is proposed that design or specification metrics can be formulated on the basis of the task margin, which is defined here as the excess vehicle 'open loop' capability relative to the 'closed loop' task performance demand. As described above, the vehicle capability will be governed by bandwidth and control power characteristics, and again it is postulated that vehicle characteristics can be defined to provide adequate performance without the need for excessive pilot compensation, ie Level 1 handling qualities. In practice, the procedure to establish the design envelope, ie vehicle capability, would begin with a specification of the required manoeuvre limit boundary, followed by a definition of the task margin, the extent of which will be driven by the increased performance required for emergency operations.

4.2 Agility requirements

Agility is concerned with the speed and precision with which an aircraft can be safely manoeuvred; a high level of agility implies rapid acceleration characteristics, which in turn imply good and rapid control responses coupled with good transient and sustained rotor thrust capabilities. The speed with which the pilot can command the desired acceleration response will be largely influenced by the transient effects associated with the vehicle's angular motion characteristics, the actuator and engine responses and the effects of aerodynamic drag. In an ideal situation free from the effects of such transients, the notion of an ideal task performance, based on the time taken to perform a given task, can be considered. The ratio of this ideal time to the actual task time achieved can be used to define an agility factor, A_F , as a measure of the level of agility.

Fig. 30 shows how the concept works in practice, using a simple sideways acceleration step as an example. For a given value for T/W, assuming that height is to be held constant the maximum acceleration can be calculated from the available bank. Assuming constant acceleration over a given distance 'S' allows the ideal time to be calculated from simple kinematics. The agility factor A_F is derived from the ratio of this theoretical minimum time to the actual task time achieved, while operating at a given T/W. Defined in this way, the agility factor represents a measure of the usable agility for a given aircraft, at a given sortie weight, flying a given task. It must be stressed here that the A_F is not an absolute measure of agility and that the values achieved will be influenced by the manoeuvre kinematics, ie acceleration, velocity, distance etc, in each case.

Fig. 31 shows how the agility factor can be expected to behave as task aggression increases and the aircraft's limiting performance, in this case the available bank, is approached. The value of 1.0 represents the ideal maximum level of agility at a given T/W. The theoretical curve shown represents the A_F's based on the ratio of the theoretical times calculated using the values of ϕ across the range, and the minimum time at ϕ_{max} . In practise the acceleration transients will act to limit the actual A_F's achieved, and handling deficiencies may constrain the pilot from exploiting the full available performance. The degree of 'levelling off' of the curve of achieved values will be influenced by the attitude response criteria discussed in the previous section. Fig. 32 illustrates the relationship between the $P/\Delta\phi$ ratio and the agility factor for a simple sideways acceleration case, from rest over a distance of 50 ft. The curve represents values calculated by assuming constant angular acceleration, a maximum available T/W ratio of 1.15, and hence a maximum angle of bank of 30°; the agility factors were derived in the manner described

above. The boundary lines demonstrate how the proposed MIL-H-8501 criteria apply in this case; the horizontal line represents the $P/\Delta\phi$ value for Level 1 boundary at a maximum angle of bank of 30°, and the vertical line represents the agility factor calculated on the basis of a 1.5 s time to achieve maximum acceleration criteria (hence, ignoring drag and inertia effects, $t_\phi = 1.5$ s and $p/\Delta\phi = 1.33$) . Thus, the hatched area represents the desirable performance for Level 1 operations. Although only a simple test case, the example given here may form a basis for making unified performance specifications expressed in terms of both the inner loop task variables, ie vehicle rates and attitudes, and the outer loop kinematic variables, ie acceleration, velocity, distance.

4.3 Flight test techniques

In order to establish the best technique and suitable task performance requirements, preliminary tests were conducted with a Puma helicopter in a sidestep manoeuvre. All tests were to be within the aircraft's operational flight envelope, and so to comply with a sideways speed limit of 30 kn, a step size of 200 ft was used. The task definition was to reposition the aircraft, from the hover to the hover in both left and right sideways flight, over the given distance, while maintaining a given task performance in height, track, heading and over/undershoot of the end point; the manoeuvre end points were determined by suitable ground markers. The objective was to establish the task time at different levels of aggression, across the full range of the aircraft's performance, where the level of aggression was to be set by the angle of bank used in the initial acceleration phase. Task parameters recorded included the pilot's control inputs, the aircraft's body accelerations, rates and attitudes, and the flight path co-ordinates. A suitable questionnaire was devised whereby the pilot could record his opinion regarding the control strategy, task cues and the aircraft's handling characteristics. In addition he was required to award Cooper-Harper ratings for the handling qualities and ratings for workload using the Bedford scale - see Tables 1 and 2.

It is of interest at this point to illustrate one of the main results from the preliminary tests. Fig. 33 shows the handling qualities ratings awarded, plotted against the observer's stop-watch timings, for the Puma sidestep tests at different angles of bank. The ratings show a marked deterioration from Level 1 to Level 3 as the task time reduces, showing how time constraints act to increase pilot workload and can expose the vehicles handling deficiencies, as shown in this case, to the point where adequate performance is unattainable. It is of interest to note that the Ref 5 task definition for the sidestep MTE contains a more relaxed requirement for height keeping performance, permitting a height increase of some 20 ft as opposed to 5 ft in the RAE tests. Handling problems with the Puma were largely associated with the aircraft's poor engine and rotor governing characteristics, particularly noticeable in manoeuvres like the sidestep where large variations in power demand are necessary. The problem was particularly exposed when the pilot was required to pursue an aggressive height tracking strategy in the tests; previous tests with a more relaxed requirement of 10 ft for height keeping had not revealed significant deficiencies in this aircraft. This example serves to underline the importance of the task performance demands and manoeuvre end point constraints to handling and performance testing of this nature.

Following the initial tests, similar trials with a Lynx were carried out. In this case the tests were extended to include sidesteps of 50, 100, 150

and 200 ft to gain a wider insight into the effect of 'time loading' on the vehicles handling and performance. A further series of tests involved a 'quickhop' manoeuvre, which is essentially the same as the sidestep manoeuvre but in the fore and aft axis. For the quickhops the tests included step sizes of 150, 300 and 600 ft to give test points in the range from 0-45 kn. Fig. 34 shows the course layout adopted in each case and also the essential features in the task definition. To allow a wide matrix of test points, because of the likely performance constraints placed by manoeuvre power limitations and the aircraft's out-of-wind operational limits, tests were conducted at a relatively low AUW and in wind speeds of less than 10 kn. The aircraft's stabilisation system was also introduced as a test parameter; for the Lynx, the aircraft's Automatic Flight Control System (AFCS) provides stabilisation in pitch, roll and yaw. The system has been shown to introduce some measure of rate damping, and again because of the likely effect on the performance, the tests were flown both with and without the AFCS engaged.

4.4 Results

In the event, the simple tasks described proved to be very exacting, both in terms of the piloting effort required and also the demands on the aircraft's handling capabilities. Although the two tasks are primarily roll and pitch control exercises respectively, in practice they are multi-axis tasks requiring large, carefully co-ordinated inputs from all controls. Above all, the tests clearly demonstrated the way in which pilot workload and task performance were strongly influenced by the handling qualities and how the level of agility was inhibited. With respect to the level of task aggression, in general the tests were pursued until the pilot's ratings for handling qualities reached the level 2-3 boundary. To give some idea of the scope of the tests, Fig. 35 gives some sample Lynx results, in the form of phase-plane plots of the rates versus attitudes, for the quickhop and sidestep tests. In both cases, as the pilot's demand increases, there is a marked increase in workload accompanied by a deterioration in the vehicle's handling qualities. The full picture of the manoeuvre demands is shown in Fig. 36, again for the Lynx quickhop and sidestep tests. The plots give a complete summary of the pilot's primary control activity, expressed in terms of the ratios of stick rates to stick displacements, plotted against the stick displacement in each case. The associated actuator responses and finally the vehicle's attitude responses are also given, and expressed in similar terms. These results reflect the high level of aggression the pilot was able to achieve, particularly for the sidesteps where for small amplitude control inputs, the $P/\Delta\phi$ values reached levels almost equivalent to the vehicle's open loop bandwidth, ie limit of vehicle capability.

The main handling and performance results are summarised in Figs. 37-41. Two subject pilots were used in the tests and for convenience they are referred to as P1 and P2 respectively. The results illustrated in Fig. 37, for pilot P1 flying the Lynx and Puma in the 200 ft sidestep tests, represent the task time, agility factor, peak roll rates and the ratio of peak rate to the roll attitude change for each test point, plotted as a function of the initial bank angle. For clarification, the task time was measured from the time of the initial cyclic control input to the point at which the control activity had subsided to the level at the initial hover condition. Task performance was checked for compliance with the required standard given in the task definition. Fig. 38 shows P1's results for all of the Lynx sidestep tests, for the unaugmented cases. Fig. 39 presents the HQR's, for both P1 and P2, returned for all of the

Puma and Lynx sidestep tests, again as a function of the initial angle of bank. Figs. 40 and 41 illustrate corresponding results for the quickhop tests over the range 150-600 ft.

4.5 Discussion

Agility and performance aspects

As expected, the agility factors increase as the pilot exploits more of the vehicle's acceleration performance viz increasing bank/pitch angles. The decrease in agility factor with reducing stepsize can be attributed to the greater proportion of time spent in the entry and settling phases of the manoeuvre. Similarly, the characteristic 'levelling off' in the agility factors observed at the higher attitudes is due in part to the increased effect of the acceleration transients, but in particular to the deceleration and settling transients in the final stage of the manoeuvre and the increased handling problems experienced by the pilot in attempting to reduce task times while maintaining the task performance. Overall, for both the sidesteps and quickhops the level of agility was dominated by the performance in the final stages of the manoeuvre; it was at this point that the handling problems were most evident, leading to reduced levels of aggression in terms of the $P/\Delta\phi$ ratios achieved. In this respect, pilot judgement had a significant effect on the degree of scatter achieved in the results, for both the subjective and numeric data, ie HQR's and agility factors. If the deceleration was too early the task time increased, and if left too late then the pilot was forced to adopt a more aggressive strategy to avoid overshooting the end marker. From this standpoint, for the Lynx the 100 ft sidestep and the 300 ft quickhop appear to be the optimum distances in terms of the pilot's control strategy and the level of agility achieved, ie agility factors closer to those for the 150 ft sidestep and 600 ft quickhop respectively. Notably, the $P/\Delta\phi$ ratio for the 100 ft sidesteps increased with initial bank, whereas for most runs the ratios decreased with initial bank. Typically roll and pitch rates used in the Lynx were some 50% higher than used in the Puma during the reversal and final stages of the runs, where roll and pitch rates in excess of 60°/s and 40°/s respectively were achieved. In comparison to the Puma, pilots achieved higher agility factors when flying the Lynx, reflecting a time advantage of some 1-2 s for this aircraft, depending on the stepsize. For the Lynx, the vehicle's augmentation had little impact on the level of agility, although, as discussed, later there were differences in handling qualities and levels of workload recorded. Although pilots noted the 'crisper' rate responses of the unaugmented aircraft, settling transients, due to cross-coupling effects, tended to cancel out any gains in performance.

The requirements for roll and pitch response characteristics, as proposed in Ref 5, were discussed in the previous section. For comparison, Fig. 42 shows a selection of test points superimposed on the specification formats, previously shown in Fig. 28. The pairs of values represent HQR's for the augmented Lynx sidestep and quickhop tests at maximum task aggression; the values correspond to pilot ratings for the roll or pitch axis alone followed by a multi-axis rating. In all cases the results exceed the Level 1 'acceptability' boundary for the $P/\Delta\phi$ or $Q/\Delta\theta$ values but fail to meet the overall handling assessment for the MTE's, relative to the requirement for Level 1 HQR's. The Level 2 HQR's for the single axis ratings reflect the size of control inputs required and the high stick forces encountered, despite the fact that the Lynx cyclic control load characteristics satisfy the Level 1 requirement for stick forces stated in Ref 5. The Level 2 multi-axis ratings reflect the overall deterioration in

the handling qualities and the high level of workload. To some extent this result can be attributed to differences in the task definitions. Significantly, the Ref 5 MTE's are not based on specific manoeuvre stepsizes with specific end point constraints; instead, they contain a requirement to accelerate to and from a given translational speed using the maximum available performance. Also, the task performance requirements allow a wider error margin in height and heading deviation; for height, a start height of 20 ft is given as opposed to 25 ft and 50 ft in RAE's sidestep and quickhop tests, and the acceptable margin for height gain is 22 ft as opposed to 5 ft; requirements for holding heading are ±25° and ±15° respectively. Inevitably, the differences described here will have a critical impact on the pilot's control strategy and influence his assessments of the handling qualities. While it is accepted that the lower start height criterion is more representative of the operating environment, the more exacting task performance requirements in RAE's test were instrumental in exposing the two aircrafts main handling deficiencies; poor engine response characteristics in the Puma and weak tail rotor control in the Lynx.

Handling and control aspects

Limitations in the level of performance the pilot was prepared to exploit were mostly linked to the high levels of workload experienced as the level of task aggression increased, viz. ϕ_{START} , and the degradation of the handling qualities to the Level 2-3 boundary. In addition, as the translational speed increased and the task times reduced, the pilot had greater difficulty in avoiding overshooting the endmarker, particularly in the shorter manoeuvres. For the sidesteps, the perceived encroachment of the aircraft's sideways velocity limit was also a problem. Handling problems were mostly encountered in the deceleration phase of the run where large and rapid changes in power demand were necessary to control height and re-establish the hover. As intimated above, the Puma's poor engine response characteristics created the potential for large rotorspeed droop and subsequent loss of height and yaw cortrol. Weak control sensitivity in lateral and longitudinal cyclic was also a contributory factor to the ratings returned for the Puma. For the Lynx, the yaw control was the main problem, particularly in a right sidestep where encroachment of the control margin established a definite performance limit. Transient over-torquing also proved to be a limiting factor in the Lynx tests, and again this problem was most apparent in the sidestep deceleration phase where the maximum roll attitudes were encountered.

The handling problems described here were largely exposed by the aggressive control strategy required to rapidly decelerate the aircraft to avoid overshooting the end marker. Pilot judgement was a critical factor in this, for, as mentioned above, in the words of the pilot "if left too late, large attitudes were required and handling deficiencies became apparent". Referring to Figs. 39 and 41, pilot ratings for handling qualities reflect the difficulties experienced and in all cases show a rapid deterioration as task aggression increases, in some cases attaining the Level 3 regime. Ratings from both pilots can be seen to be in broad agreement, and for most cases, the augmented Lynx was awarded ratings at 1-2 points below (better than) the unaugmented aircraft, reflecting the improvement in handling qualities due to the reduced effect of control cross-couplings. There are however several exceptions, notably the differences in the pilots' ratings for left and right sidesteps and P2's increased ratings for the augmented Lynx in the 300 ft quickhops. Addressing the first point, the numerical results, ie agility factors and $P/\Delta\phi$ ratios, show that P2 tended to fly less aggressively in the left sidestep because of the reduced field of view

across the cockpit. Pilot comment also reveals that P1 tended to pursue heading control more aggressively and flew to tighter error margins, hence he was more critical of yaw control problems encountered in the left sidestep than P2. In the second case, the inconsistency in P2's ratings for the augmented and unaugmented aircraft can be explained by the increased level of confidence the pilot had in the augmented machine, and again the numerical results reflect an increased level of pilot aggression for the former case.

Ratings for pilot workload were generally within one rating of the handling qualities ratings for each test point. To a degree, this is a reflection of the pilot compensation required for the aircraft's handling deficiencies, although other factors such as the task cues and observance of the aircraft limits obviously exert an influence. Outside visual cues were used for all aspects of the task performance, ie track, height and for holding attitude and heading; where there was a need to look at the cockpit gauges, particularly in the Lynx where the pilot had to monitor the main rotor torque limits, then workload increased and the task performance was inhibited. Pilot workload in the quickhop tests was particularly influenced by the difficulty in controlling height and the restricted field of view from the cockpit; for nose down attitudes greater than 20-25° and nose-up attitudes greater than 5-10° the pilot lost sight of the end markers. Not surprisingly, workload ratings of 7-8 were returned for the most aggressive quickhop test points.

To conclude this section, it is of interest to make a more direct examination of the influence exerted by the aircraft's handling qualities in setting the level of agility achieved. Previous discussion has shown how both agility and handling are strongly influenced by the level of task aggression, as determined by the requirement to achieve a given task performance within a reducing time scale. To complete the picture, Fig. 43 shows the variation of pilot HQR's with agility factor for both Lynx and Puma sidestep and quickhop tests. The data clearly illustrate the higher agility factors achieved in the Lynx but at the expense of a degradation in the pilot ratings, particularly for the quickhop. On the basis of the results shown here, it is difficult to make recommendations as to the desirable level of agility, but clearly, for future battlefield helicopters the objective must be to achieve maximum agility with Level 1 ratings. The strong sensitivity of the task performance and HQR's to task aggression demonstrated in the results presented in this paper, emphasizes the care that must be exercised when defining flight tasks for compliance testing of future types. It is essential that such tests adequately reflect the most demanding aspects of the operating environment, both in terms of a realistic task performance requirement and also in relation to factors such as pilot judgement and manoeuvre endpoint constraints; obviously care must be taken not to over specify the performance requirements. Although many of the test techniques are exacting, it is considered that testing of the nature and scope adopted by RAE is essential in order to enable a full and realistic assessment of the aircraft's flying qualities.

5 CONCLUSIONS

5.1 Small amplitude criteria

The RAE Bedford Puma flight research helicopter has been documented in terms of various forms of bandwidth criteria, proposed over the last few

years. Variations in flight condition, loading and augmentation configuration have been used to give a wide range in bandwidth and associated handling qualities parameters such as equivalent time delay and phase slope. This study has highlighted areas of deficiency or inconsistency in the various forms of bandwidth criteria proposed. RAE experience with flight test and analysis methods for compliance demonstration is described. The relevance of the method of equivalent systems modelling as an adjoint to that proposed elsewhere for rotorcraft, is highlighted. Additionally it is suggested that real-time telemetry revised during open-loop (frequency) sweep testing is used to monitor airworthiness.

(i) An attitude tracking task has been described, for pilot-in-the-loop testing. The task demonstrates a consistent, repeatable, flexible and clinical means of exploring the handling qualities that are related to small amplitude tracking tasks. The results are most amenable to analysis by spectral methods (like the methods for compliance demonstration), allowing a means of direct comparison of open-loop and pilot-in-the-loop characteristics. Potential areas of concern with the use of this task are discussed in the paper, although careful consideration of both pilot opinion and the test data show that they do not impact on the results given here.

(ii) The paper includes detailed analysis of the open-loop and pilot-in-the-loop aircraft characteristics, to identify pilot control strategy. Combined with pilot opinion, these more speculative results tend to suggest time delay as a dominant handling qualities parameter, and further, that Level 1 handling qualities are restricted to configurations with equivalent delays less than 200 ms although even this value may well be too high. A relaxation of the 45° phase margin used to determine bandwidth, to around 30° is also suggested. However, such modifications to the bandwidth criteria must necessarily be regarded as tentative, given the fact that only one vehicle type was used, and such results may be specific to the Puma configurations examined. However, these results and analysis methods point the way for future RAE research in this area which will seek to substantiate them over a wider database.

5.2 <u>Moderate amplitude criteria</u>

Flight tests have been conducted as a means of creating a database for establishing suitable agility and handling criteria for the specification of new types. This paper has presented results for two low speed, moderate amplitude manoeuvres, the sidestep and quickhop, for the RAE research Puma and Lynx flown by two subject pilots. Numerical results from the tests, together with qualitative pilot assessments, have shown the level of task performance the pilot was able to achieve, and demonstrated the degree to which factors such as the vehicle's handling qualities, act to constrain the use of the full aircraft performance. The results allow the following conclusions to be drawn.

(i) Pilot ratings for handling qualities are strongly influenced by the level of task aggression. As the task times reduced, the ratings deteriorated from the Level 1-2 boundary through Level 2 to Level 3. The two tasks, although primarily roll and pitch axis tasks, are very much multi-axis tasks and Level 3 ratings were awarded because of deficiencies in other control axes - Puma engine and rotor governing affected height control and Lynx tail rotor performance affected yaw control. Height control was a critical factor in the pilot's control

strategy for all four controls, because of cross-coupling effects and the effect on pilot aggression, hence the tight requirement for height task performance (±5 ft) had a strong influence on the level of handling qualities achieved at maximum task aggression.

(ii) Although Lynx roll/pitch control response at maximum task aggression exceeded the proposed MIL-H-8501 Level 1 criteria, pilots returned Level 2 HQR's. The sensitivity of pilot rating to task aggression reported in this paper has highlighted the need for this aspect to be taken into account during compliance testing of a new type. Moreover the conclusion of Ref 9 that tasks without terminal position and time loading constraints are inappropriate for the discrimination of handling qualities in the NOE is endorsed.

(iii) Agility factors of the order of 0.55-0.65 for the sidestep tests and 0.65-0.8 for the quickhops were achieved, but with Level 2/3 ratings. Future types should be capable of achieving improved agility factors moreover with Level 1 ratings.

(iv) In addition to the performance aspects of the tests, pilot comment has underlined the importance of basic design features such as a wide and clear field of view from the cockpit in NOE flight. Moreover, the requirement to monitor flight envelope limits through cockpit instruments significantly increases workload, and essential information should ideally be displayed via head-up or helmet-mounted displays. Finally, the power control should be free from constraints such as torque limits - a carefree power demand control would significantly reduce workload.

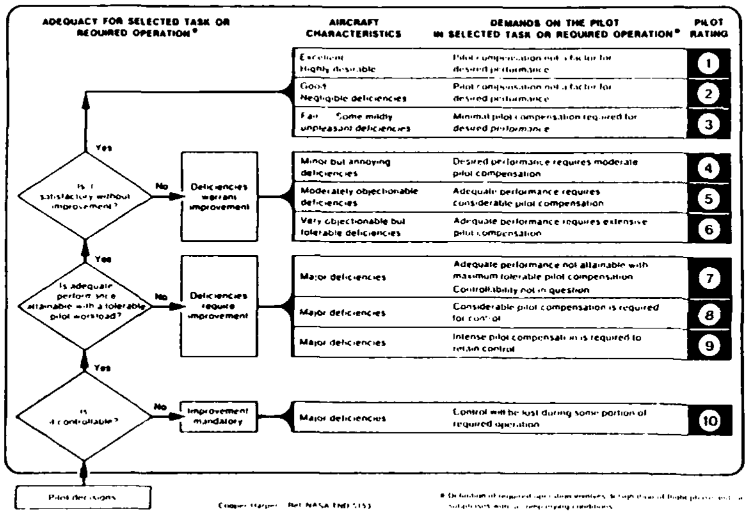

Table 1 Cooper-Harper handling qualities rating scale

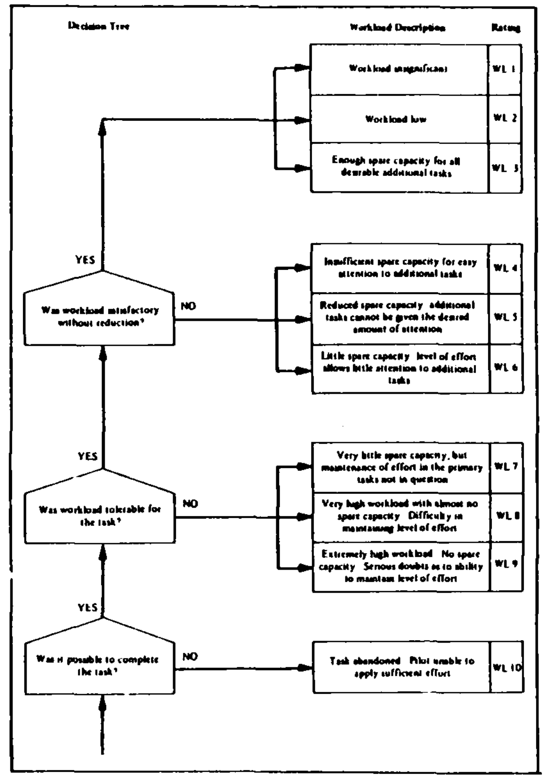

Table 2 Pilot workload rating scale

Table 3 Summary of participating pilots background and experience

Pilot	Service	Flying background	Rotary wing hours	Hours on type	Test-pilot school
P1* (Horton)	RN	Commando assault	2040	45	ETPS
P2 (Whitfield)	AAC	Anti-tank	1700	6	ETPS
P3 (Northey)	RAF	Support and royal flight	3500	100	ETPS
P4 (Kidd)	RN	Commando assault	4500	200	ETPS

*Project pilot

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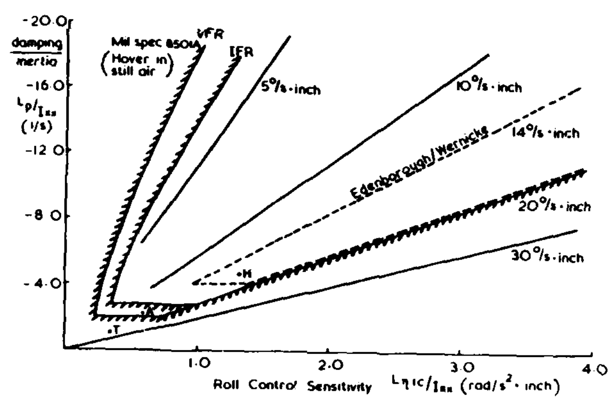


Fig 1 Roll damping/Control sensitivity criteria

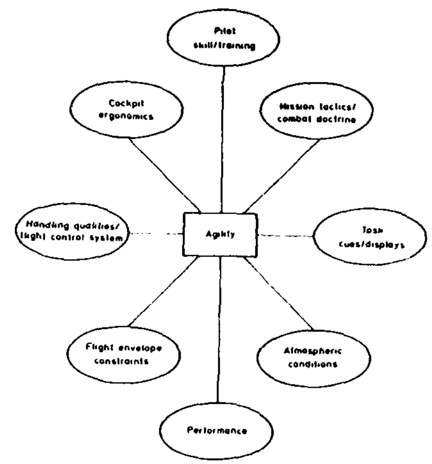


Fig 2 Factors influencing helicopter agility

Figs 3-4

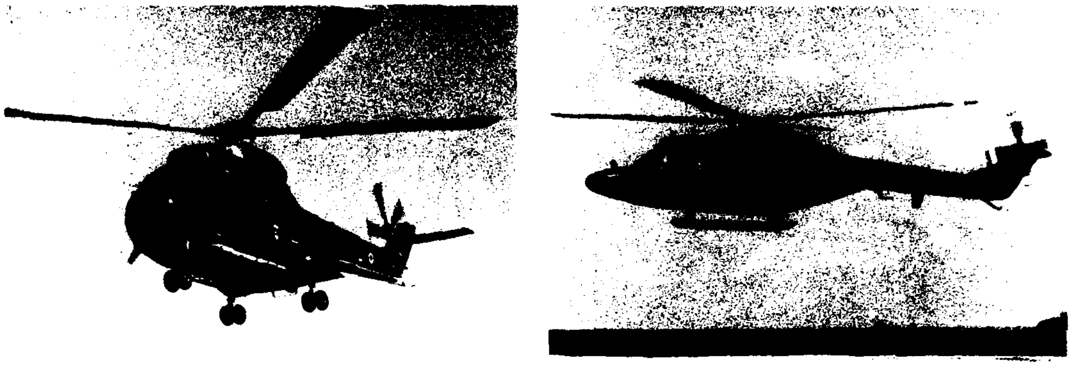
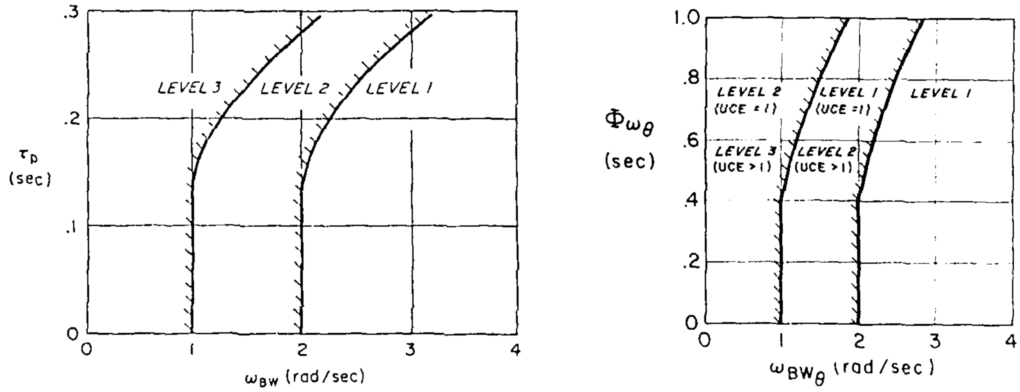
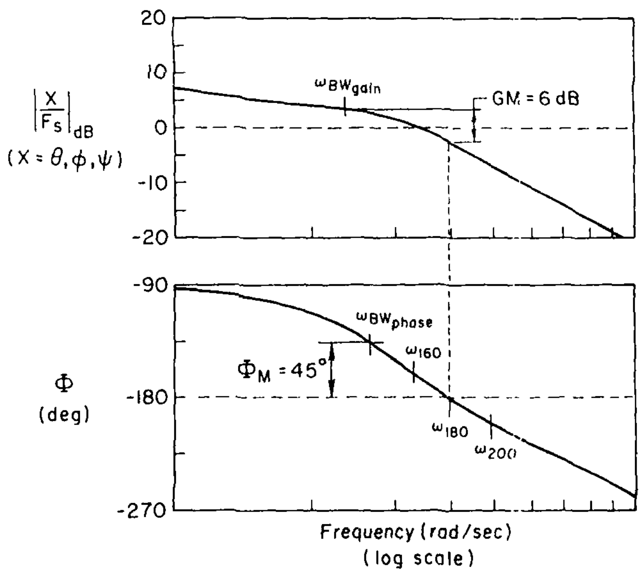


Fig 3. RAE Bedford Puma & Lynx flight research helicopters





Phase Delay:

$$\tau_p = -\frac{\Phi_{2\omega_{180}} + 180}{57.3\,(2\omega_{180})}$$

Phase Slope:

$$\Phi_\omega = \frac{40}{57.3\,(\omega_{200} - \omega_{160})}$$

Rate Response-Types:

ω_{BW} is lesser of $\omega_{BW_{gain}}$ and $\omega_{BW_{phase}}$

Attitude Response-Types:

$\omega_{BW} \equiv \omega_{BW_{phase}}$

Fig 4. Phase slope and phase delay bandwidth criteria

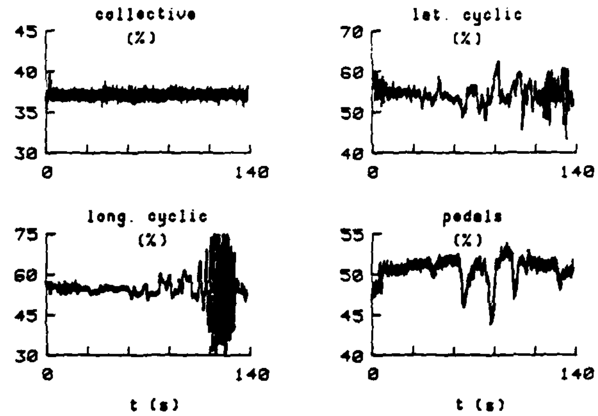


Fig 5 Control input time histories, augmentation disengaged, 80 kn

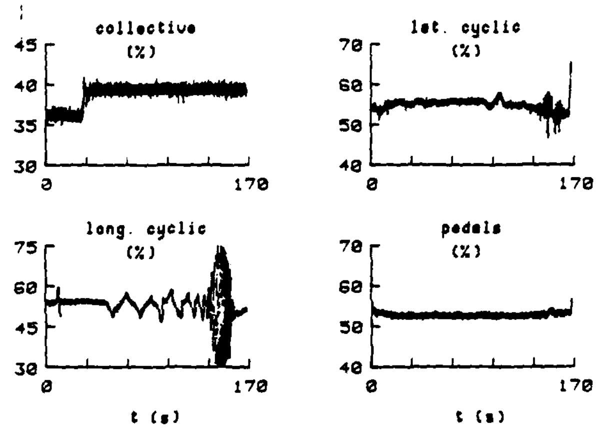


Fig 6 Control input time histories, augmentation engaged, 30 kn

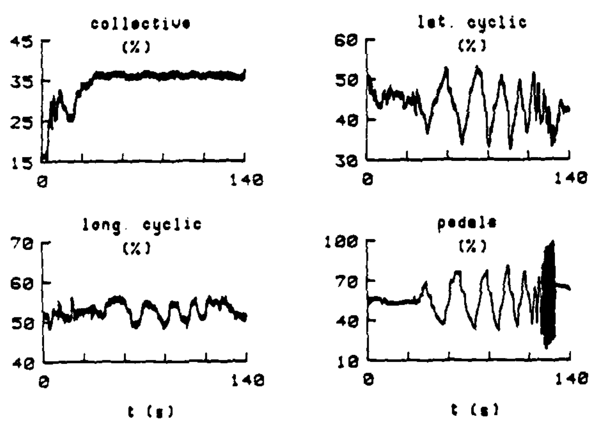


Fig 7 Control input time histories, augmentation engaged, 80 kn

Figs 8-9

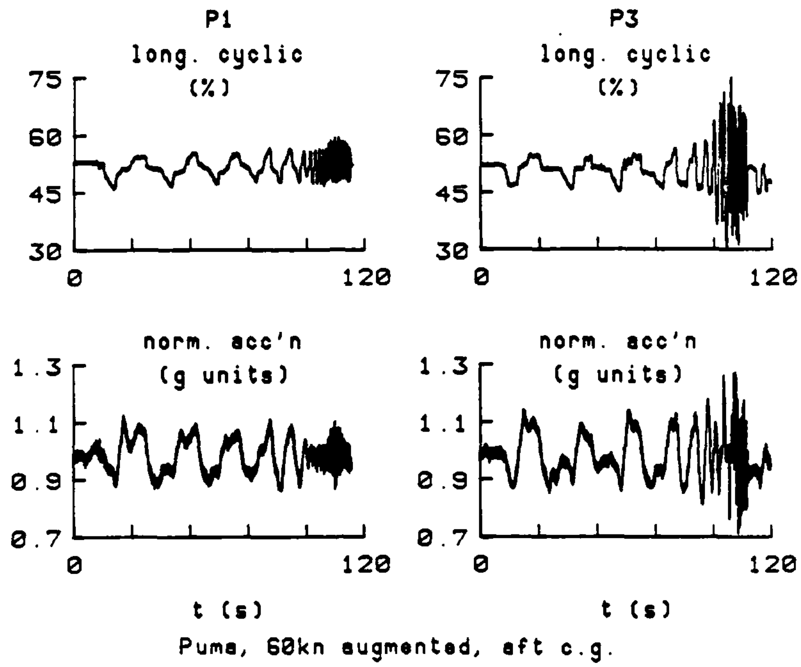


Fig 8 Comparison of frequency sweep inputs made by two pilots

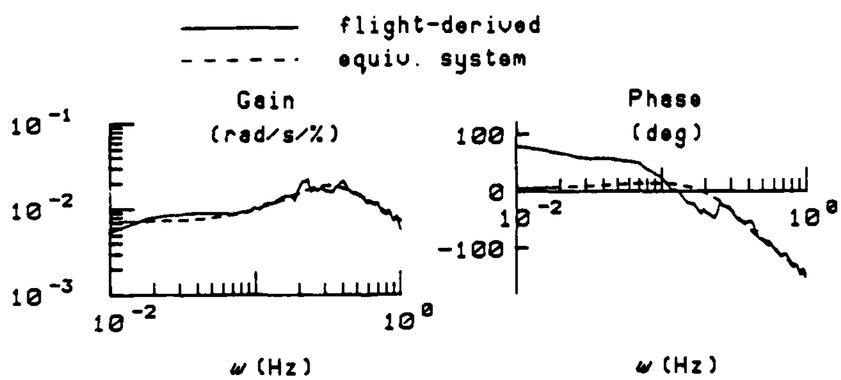
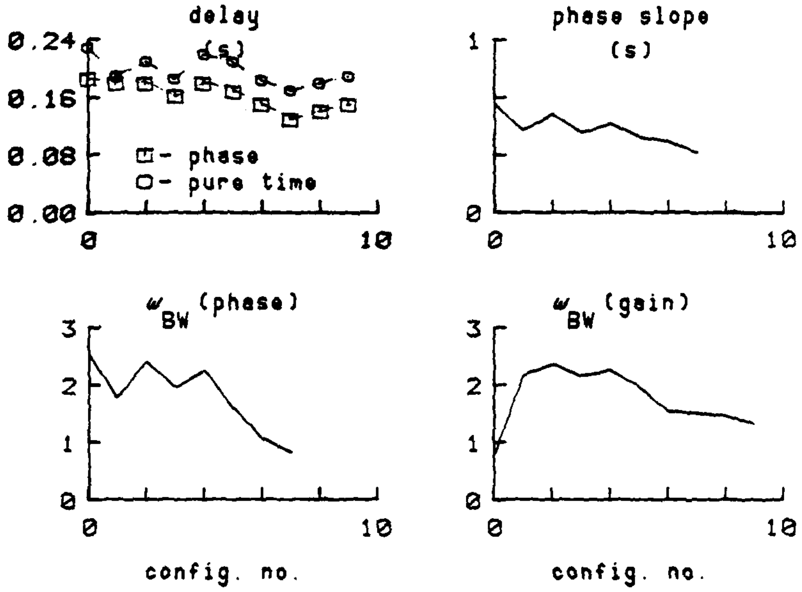


Fig 9 Puma pitch rate to longitudinal cyclic frequency response and equivalent system match - 60 kn, aft cg



0 -- 60kn augmented, forward c.g.
1 -- 60kn augmented, aft c.g.
2 -- 60kn augmented, mid c.g.
3 -- 80kn augmented, mid c.g.
4 -- 100kn augmented, mid c.g.
5 -- 120kn augmented, mid c.g.
6 -- 60kn unaugmented, mid c.g.
7 -- 80kn unaugmented, mid c.g.
8 -- [illegible] unaugmented, mid c.g.
9 -- 120kn unaugmented, mid c.g.

Fig 10 Handling qualities parameter values for each configuration

Figs 11-14

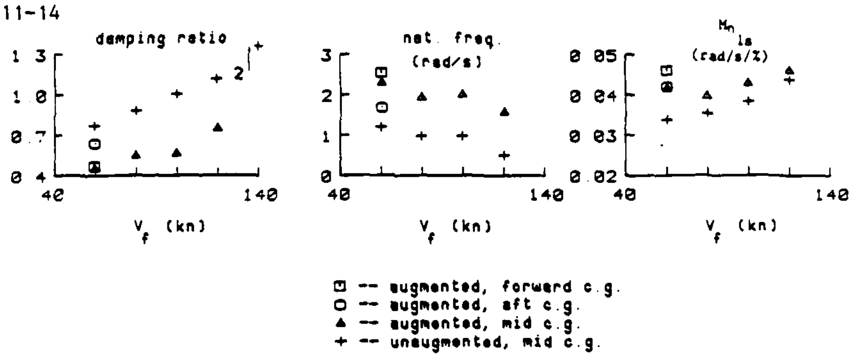


Fig 11 Identified Puma equivalent system parameters for each configuration

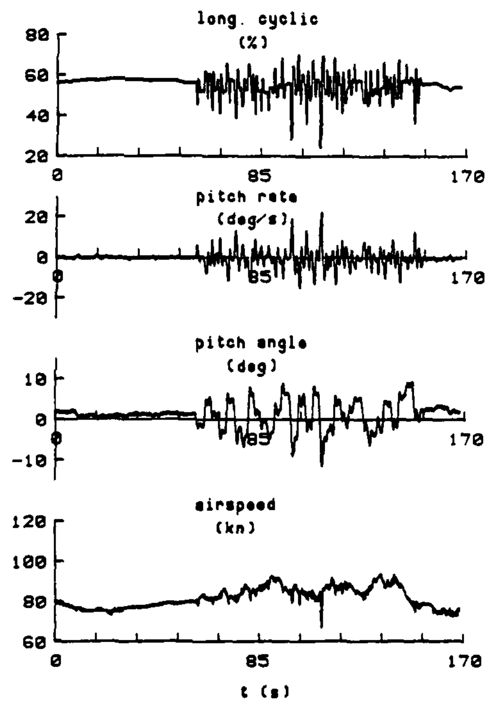


Fig 12 Time histories of control input and response during tracking Pilot P1, augmentation engaged, 80 kn

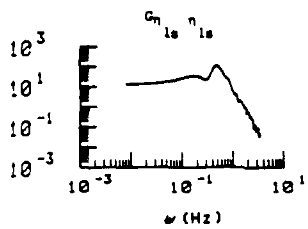


Fig 13 Longitudinal cyclic stick autospectrum. Pilot P1 augmentation engaged, 80 kn

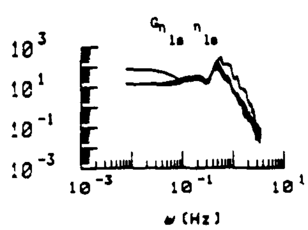


Fig 14 Comparison of longitudinal cyclic spectra. Pilots P1-P4, augmentation engaged, 80 kn

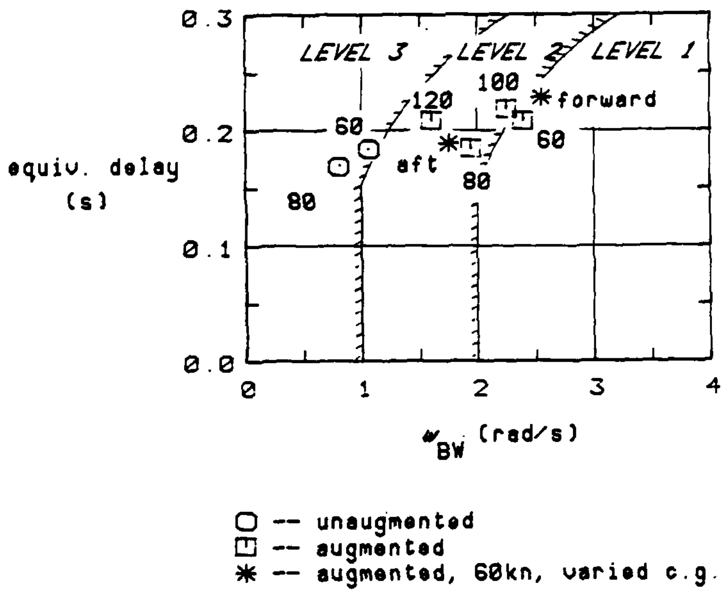


Fig 15 Puma pitch axis dynamics characterised by equivalent time delay and phase-limited bandwidth (margin = 45°)

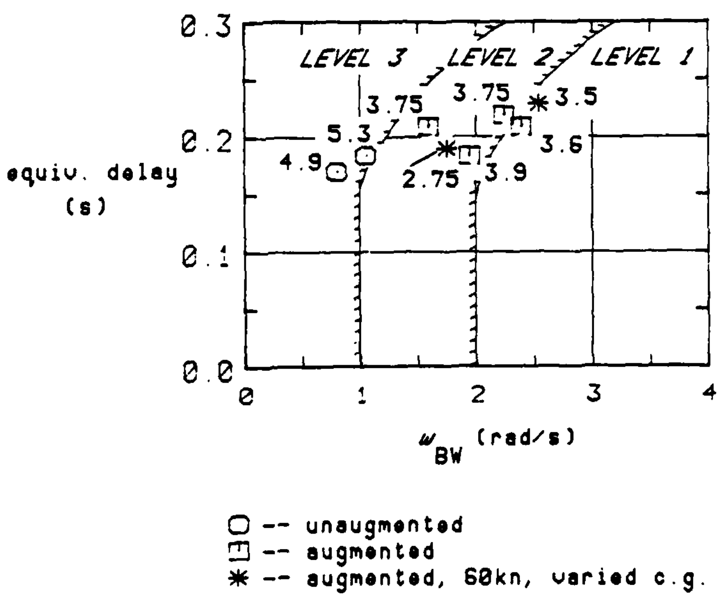


Fig 16 Correlation of Puma equiv-delay/phase-limited bandwidth characterisation with pilot assessment

Figs 17-18

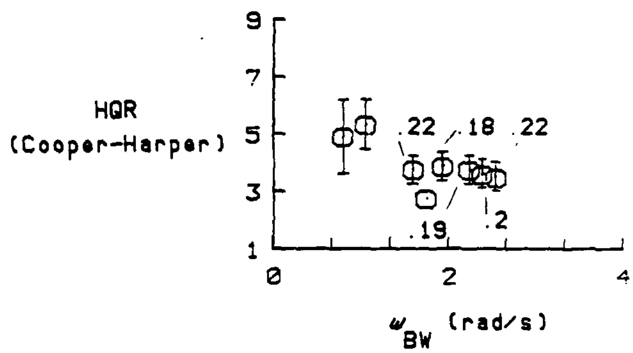
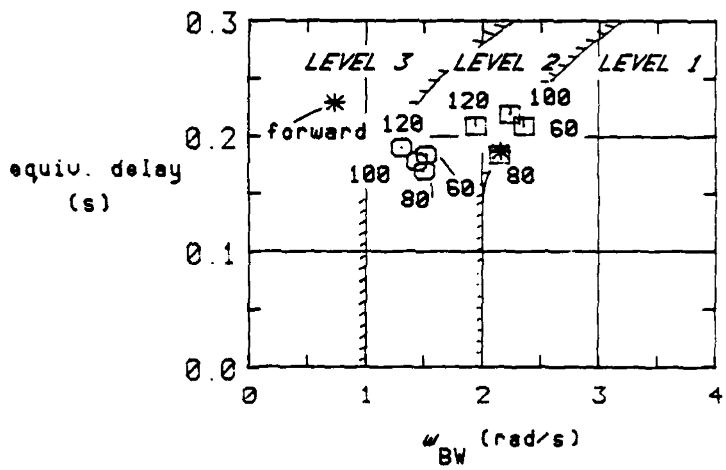


Fig 17 Variation in pilot rating with phase-limited bandwidth



○ -- unaugmented
⊡ -- augmented
✳ -- augmented, 60kn, varied c.g.

Fig 18 Puma pitch axis dynamics characterised by equivalent time delay and gain-limited bandwidth (margin = 6 B)

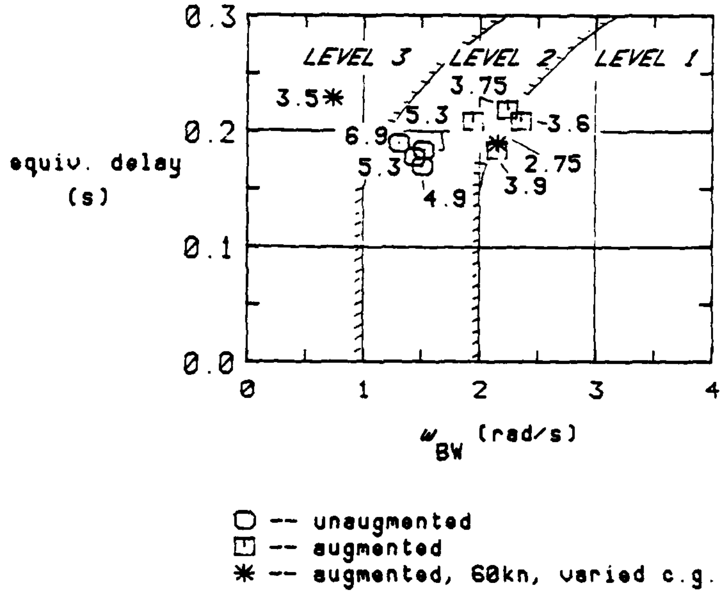


Fig 19 Correlation of Puma equiv-delay/gain-limited bandwidth characterisation with pilot assessment

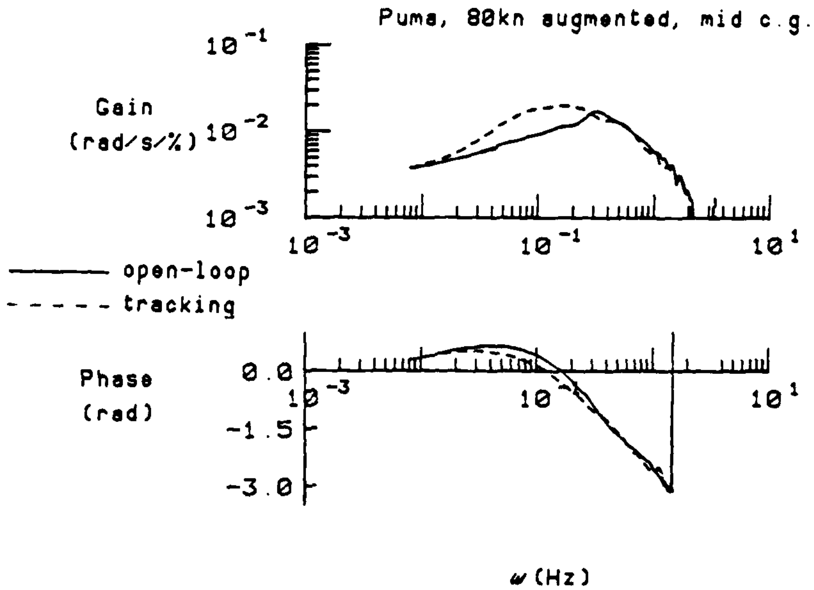


Fig 20 Comparison of open and closed-loop (tracking) pitch rate to longitudinal cyclic frequency responses
Pilot P1

Figs 21-22

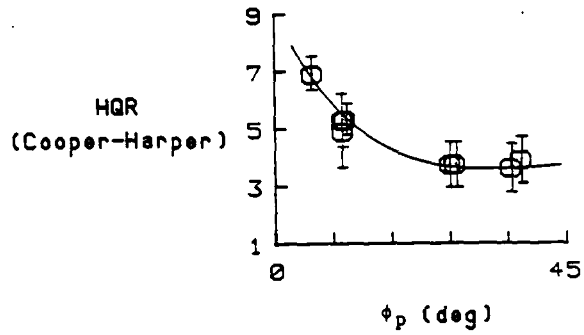


Fig 21 Variation in pilot rating with effective phase margin

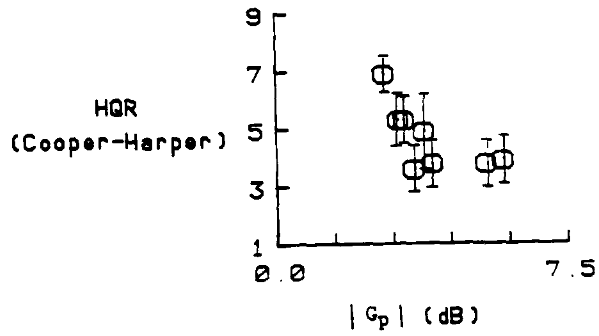
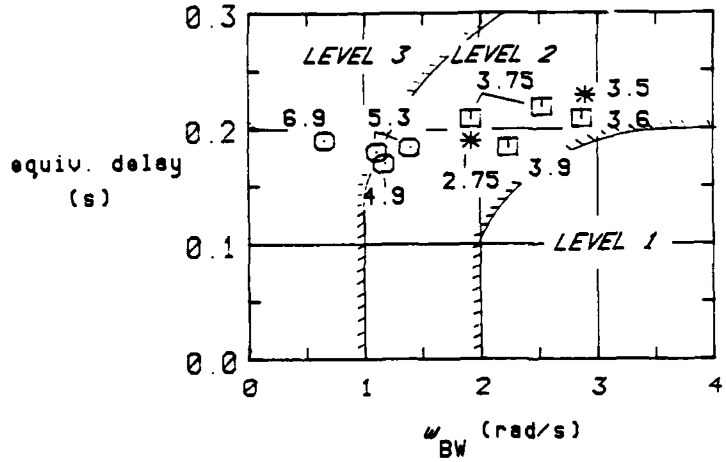
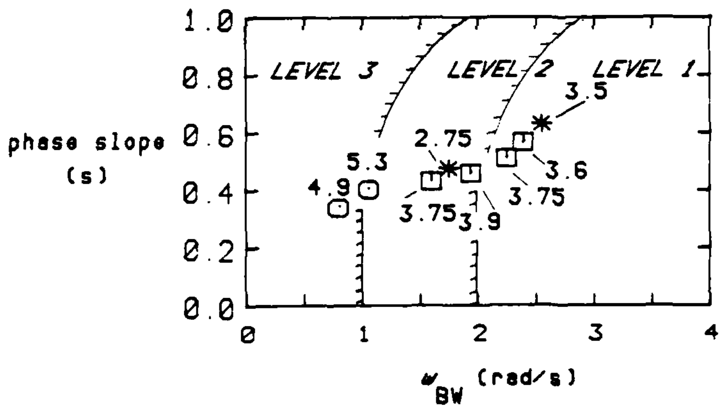


Fig 22 Variation in pilot rating with effective gain margin



O -- unaugmented
⊡ -- augmented
* -- augmented, 60kn, varied c.g.

Fig 23 Puma pitch axis dynamics characterised by equivalent time delay and phase-limited bandwidth (margin = 30°) modified Level 1 boundary



O -- unaugmented
⊡ -- augmented
* -- augmented, 60kn, varied c.g.

Fig 24 Correlation of Puma characterisation in terms of phase slope and bandwidth

TM FM 26

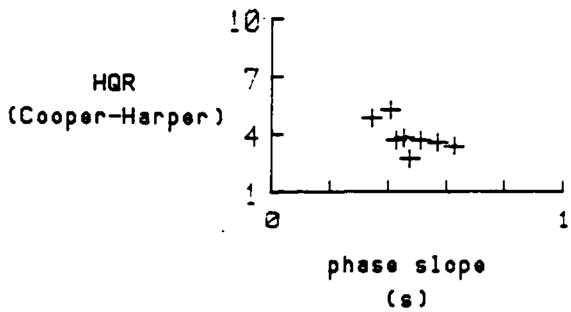


Fig 25 Variation in pilot rating with phase slope

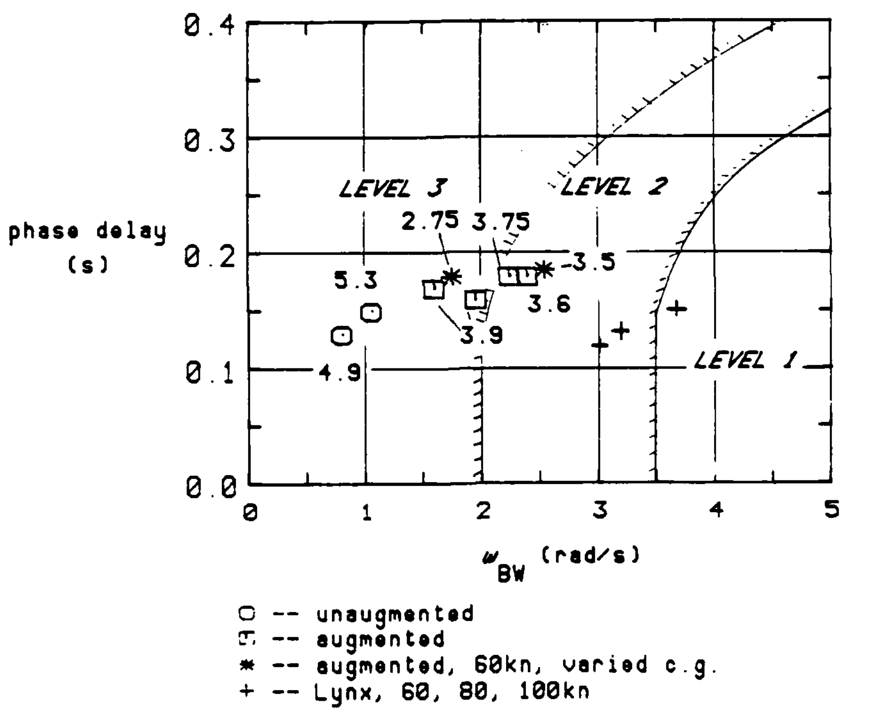


Fig 26 Puma and Lynx pitch axis dynamics characterised by phase delay and phase-limited bandwidth - latest (Ref 5) form for air-air combat

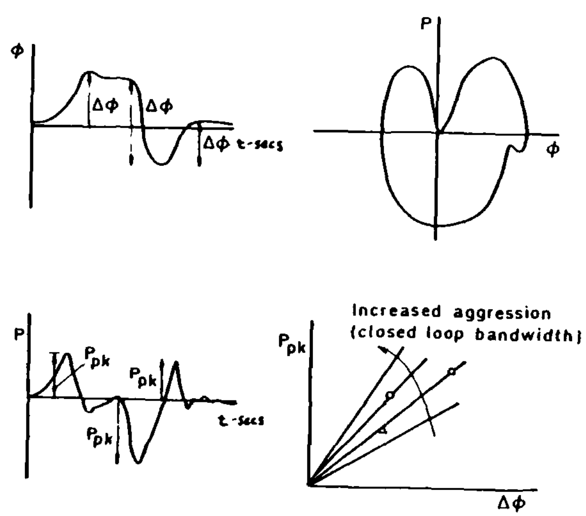


Fig 27 Roll control characteristics for a sidestep manoeuvre

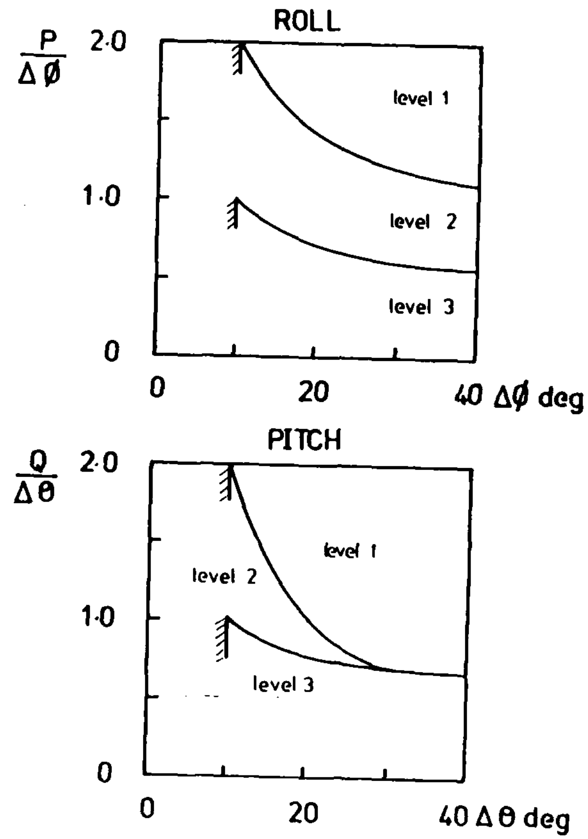


Fig 28 Proposed Mil-Spec 8501 criteria

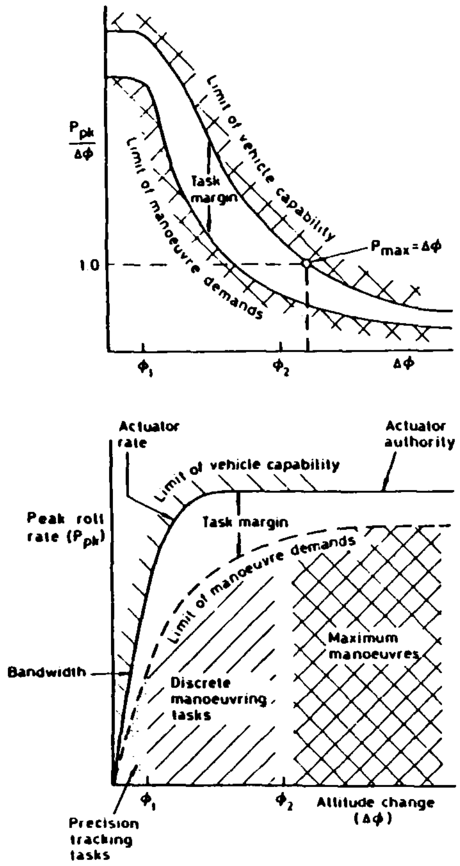


Fig 29 Manoeuvre demands and task margin for attitude dynamics

* Assume ϕ_{max} based on a 15% thrust margin:

  $\frac{T}{W} = \frac{1}{\cos\phi_{max}} \triangleq 1.15$

  $\phi_{max} = 30°$

* Assume constant accel/decel where:

  $a = \pm g \tan\phi_{max}$

* Derive theoretical manoeuvre time:

  $T_t = \sqrt{\left(\frac{4S}{a}\right)}$

* Measure task time and derive agility factor:

  $A_F = \frac{T_t}{T_a}$

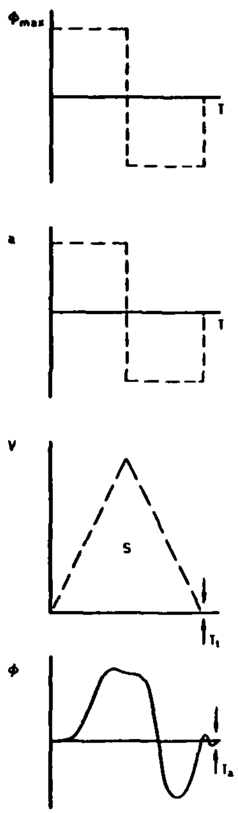


Fig 30 Agility factor derivation

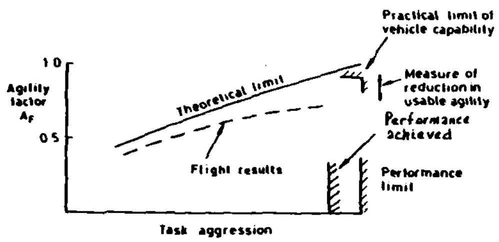


Fig 31 Variation of agility factor with task aggression

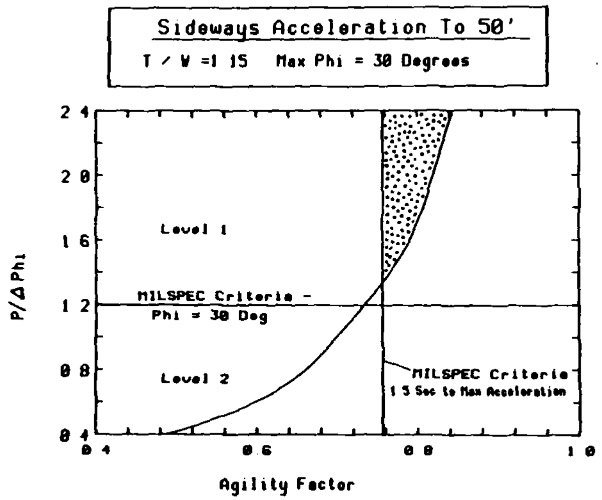


Fig 32 Variation of agility factor with attitude dynamics

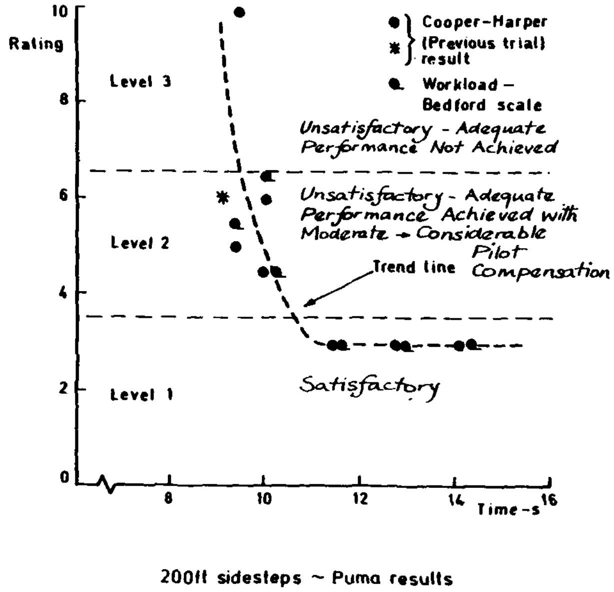
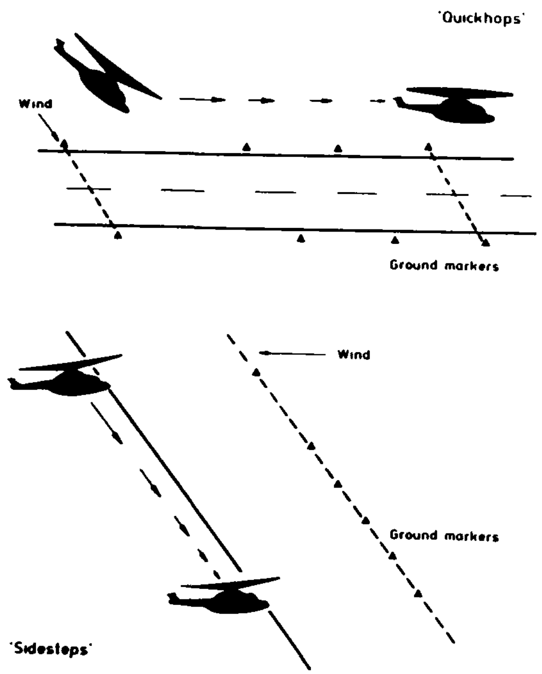


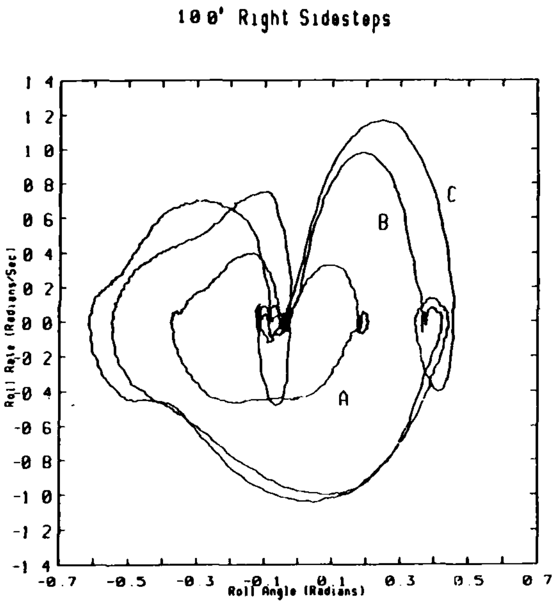
Fig 33 Variation of pilot rating for handling quality with task time



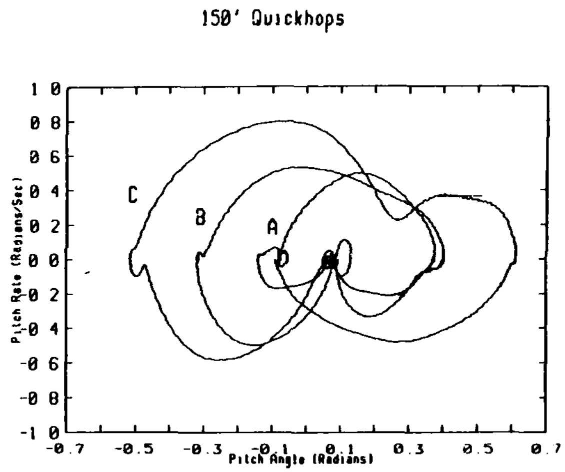
Agility Tests

- **Task definition**
  Left & right Sidesteps 50ft, 100ft, 150ft, 200ft
  ϕ_{start} = 5°, 10°, 15°, 20°, 25° — →
  Quickhops 150ft, 300ft, 600ft
  θ_{start} = 5°, 10°, 15°, 20°, 25° — →
  Establish Tmin
  Wind conditions < 10knots
- **Task performance**
  Heading ±15°, height ±5ft
  Track ±5ft, under/overshoot ±10ft
- **Data recording**
  Flightpath coords – Kine's
  Aircraft parameters – Plessey MODAS
  Pilot comment – Questionnaire
  HQR – Cooper/Harper
  WLR – Bedford scale
- **Data analysis**
  Reduce agility factors
  Closed loop bandwidth

Fig 34 Test techniques for low speed manoeuvres



		HQR	WLR
A - INITIAL Δφ = 12.6 DEG		3	3
B - INITIAL Δφ = 22.9 DEG		5	5
C - INITIAL Δφ = 28.6 DEG		5	7



		HQR	WLR
A - INITIAL Δθ = 11.5 DEG		3	3
B - INITIAL Δθ = 21.8 DEG		4	4
C - INITIAL Δθ = 31.5 DEG		6	7

Fig 35 Attitude control characteristics for Lynx in low speed manoeuvres

Fig 36

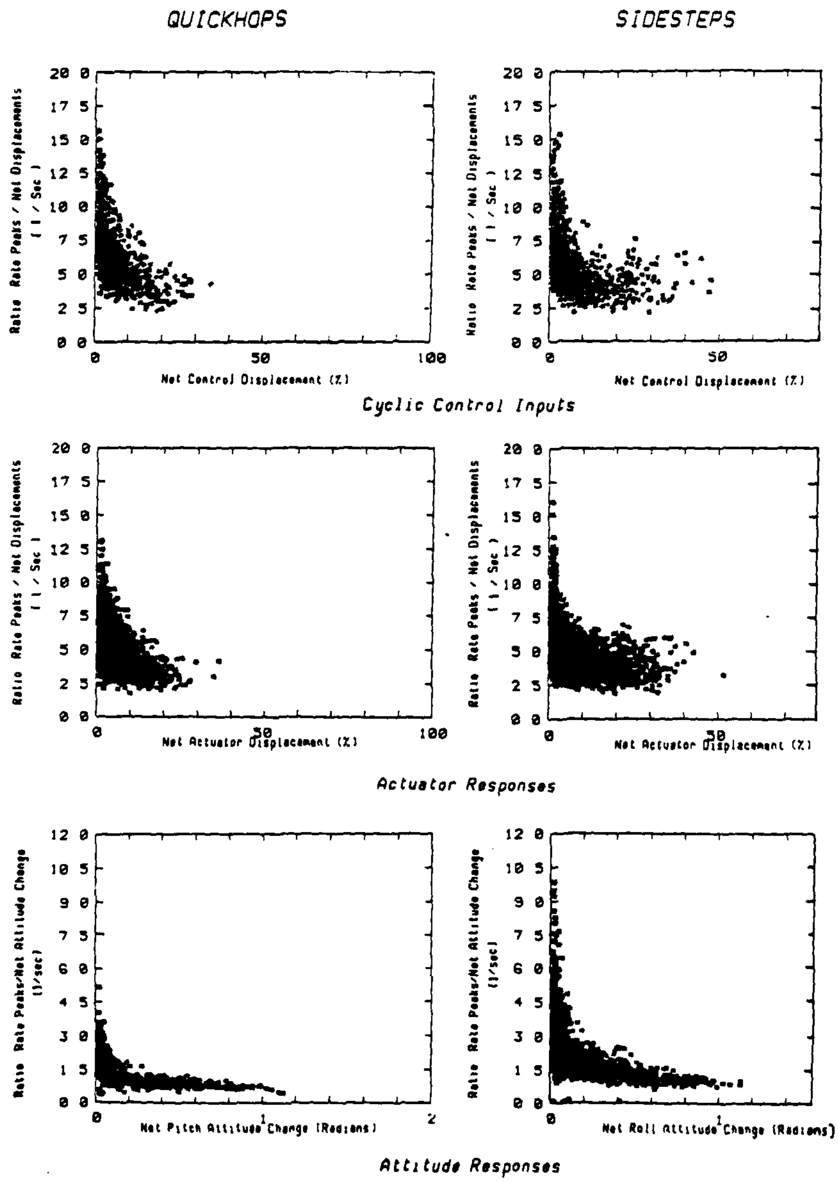
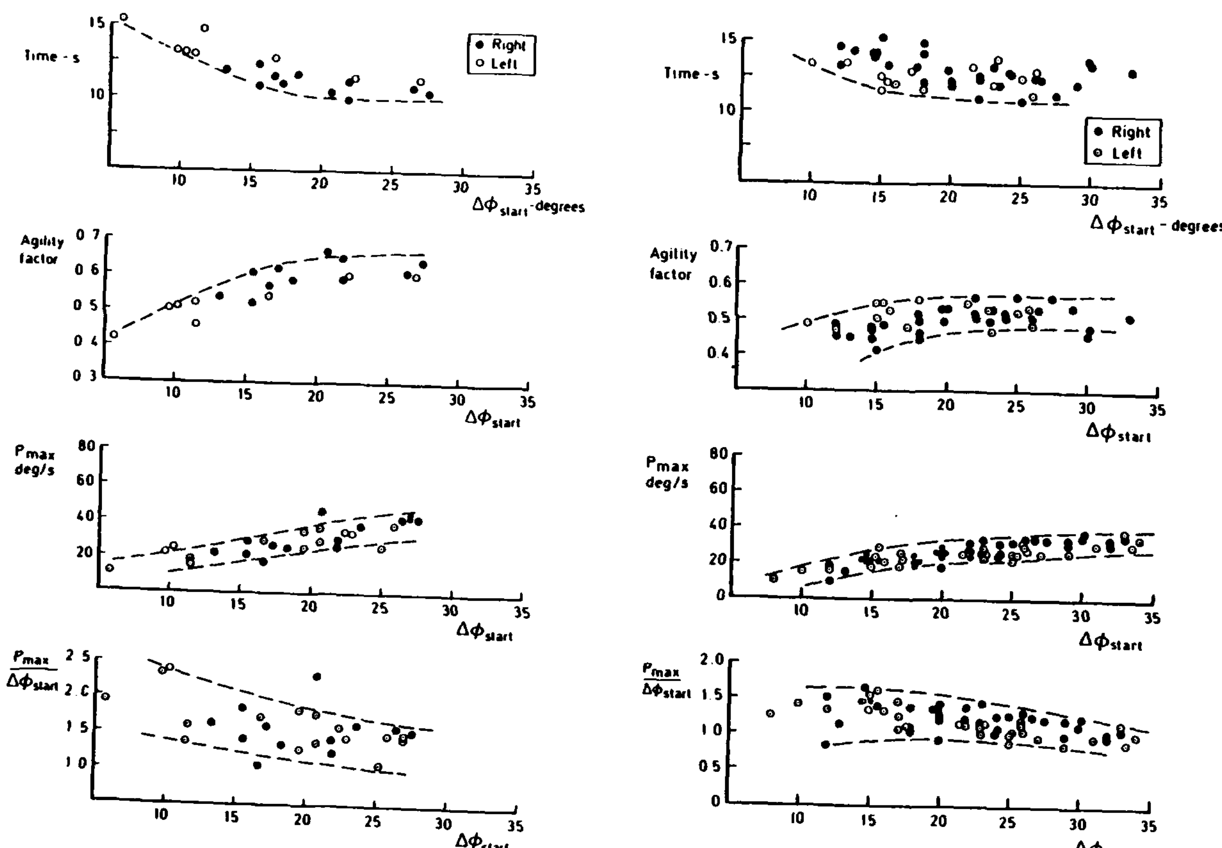


Fig 36 Summary of Lynx attitude control demands in low speed manoeuvres

TM FM 97

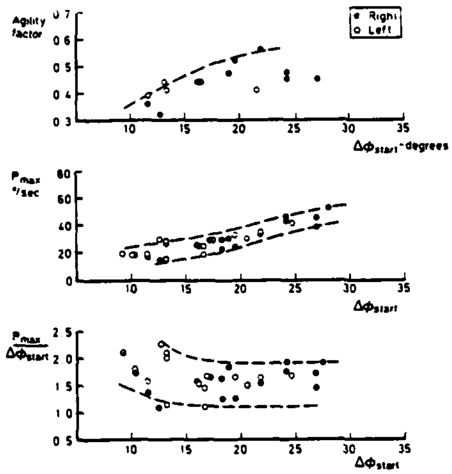


LYNX — 200ft Sidesteps; CAC & AFCS disengaged
Pilot — P1; Flights 139A & 162

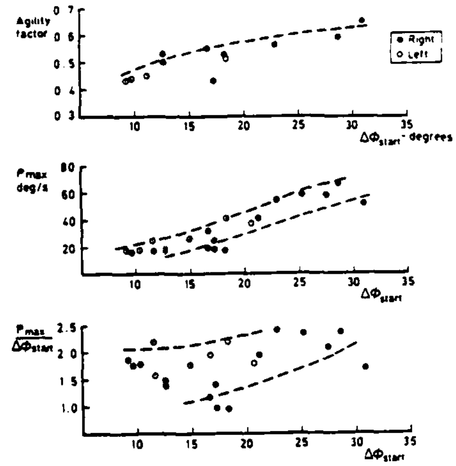
PUMA — 200ft Left & Right Sidesteps; AFCS engaged
Pilot — P1; Flights 690 & 715

Fig 37 Comparison of Lynx and Puma agility for 200 ft sidestep

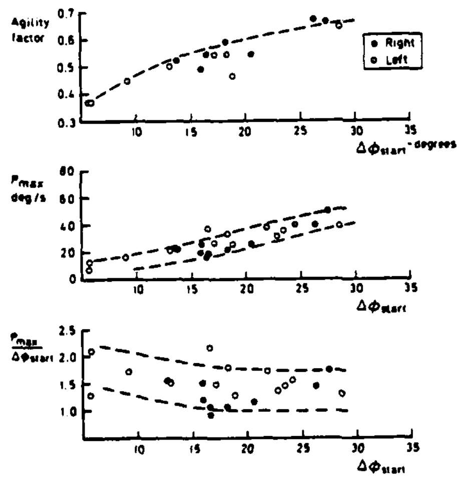
Fig 38



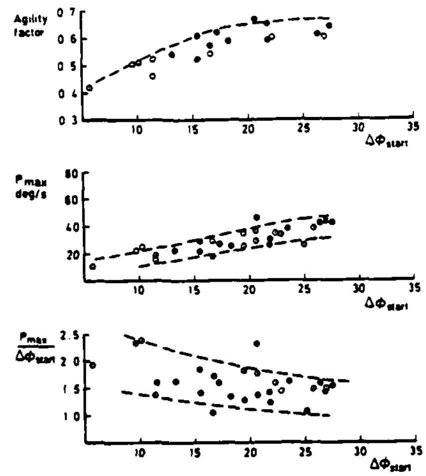
LYNX — 50ft Sidesteps; CAC & AFCS disengaged
Pilot — P1; Flights 138 & 139A



LYNX — 100ft Sidesteps; CAC & AFCS disengaged
Pilot — P1; Flight 139A



LYNX — 150ft Sidesteps; CAC & AFCS disengaged
Pilot — P1; Flight 162



LYNX — 200ft Sidesteps; CAC & AFCS disengaged
Pilot — P1; Flights 139A & 162

Fig 38 Lynx agility in sidestep tests

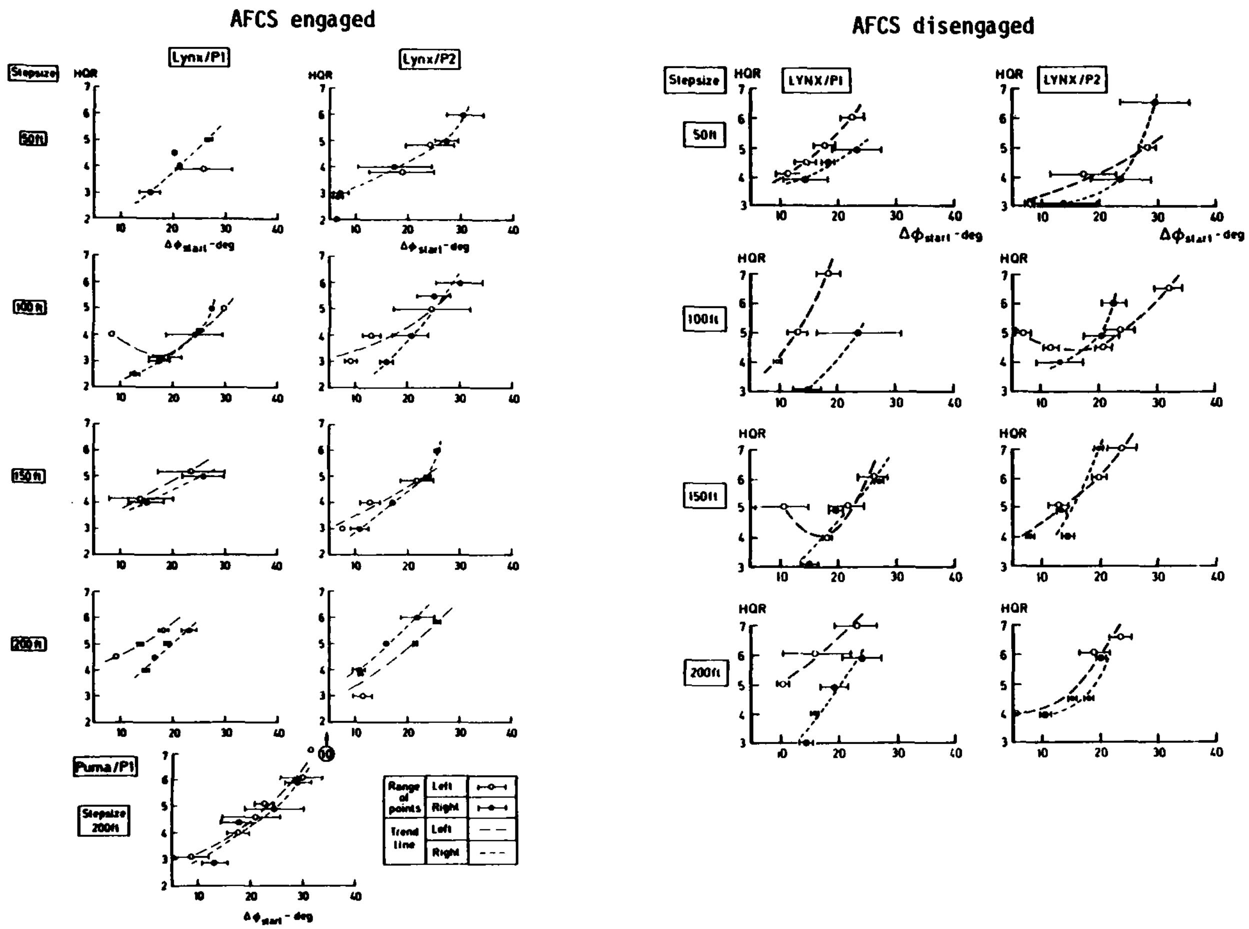
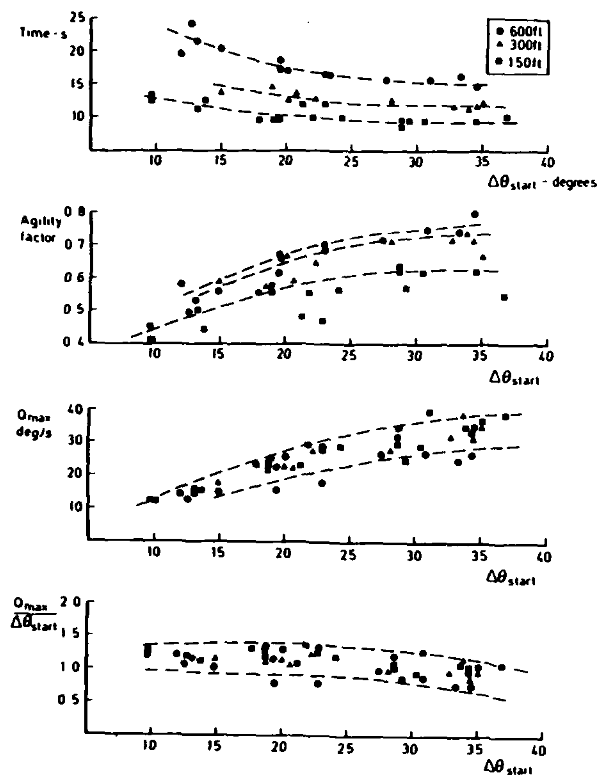
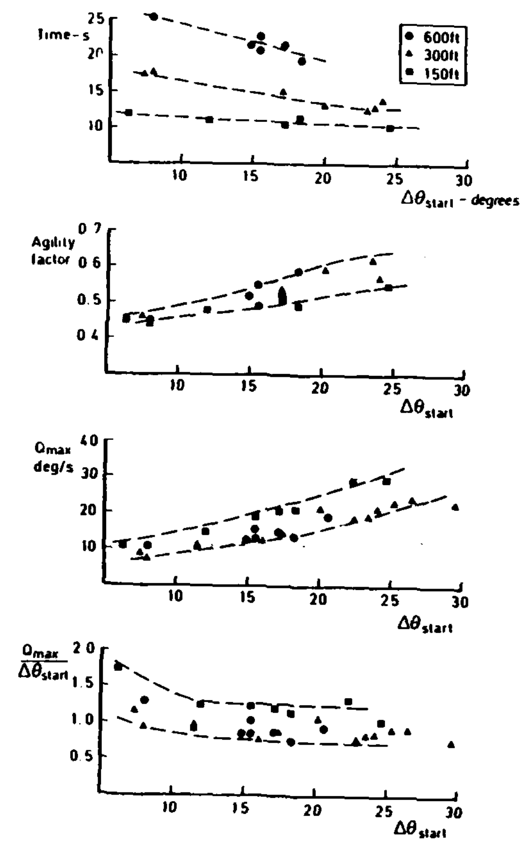


Fig 39 Handling qualities ratings for sidestep tests



LYNX – Quickhops, CAC & AFCS disengaged
Pilot – P1, Flights 131 & 132



PUMA – Quickhops / AFCS engaged
Pilot – P1, Flight 729

Fig 40 Comparison of Lynx and Puma agility for quickhop tests

AFCS disengaged

AFCS engaged

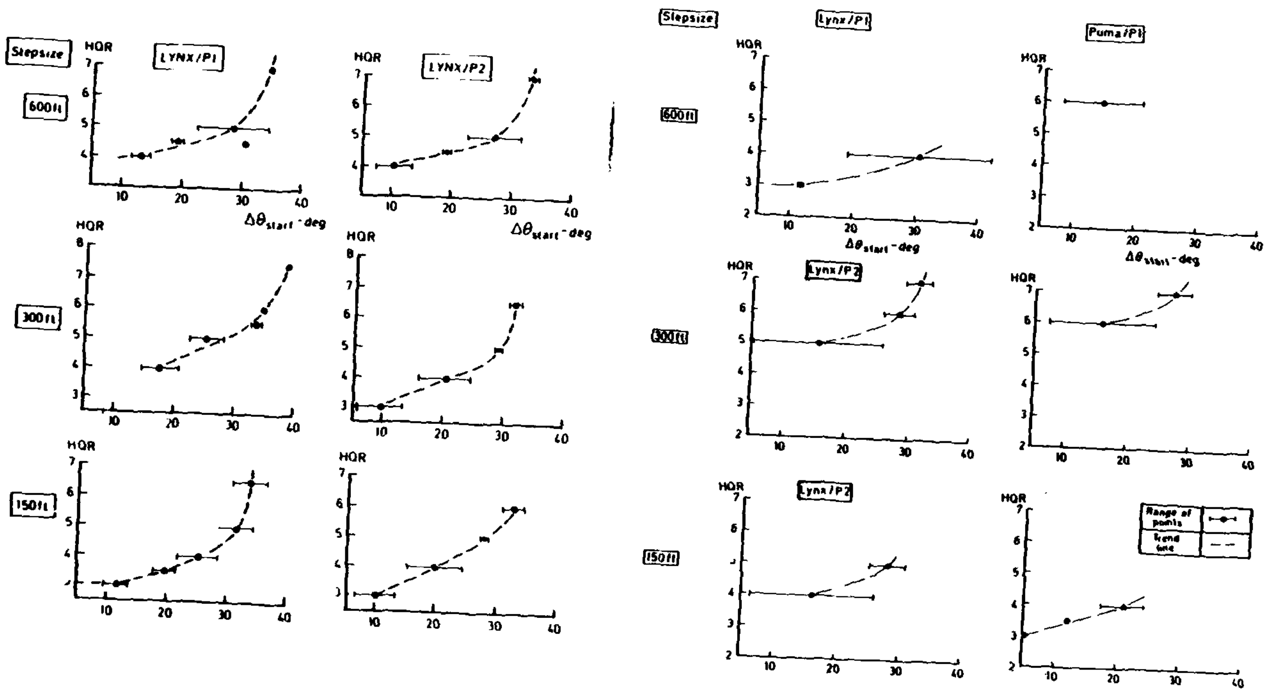


Fig 41 Handling qualities ratings for quickhop tests

Figs 42-43

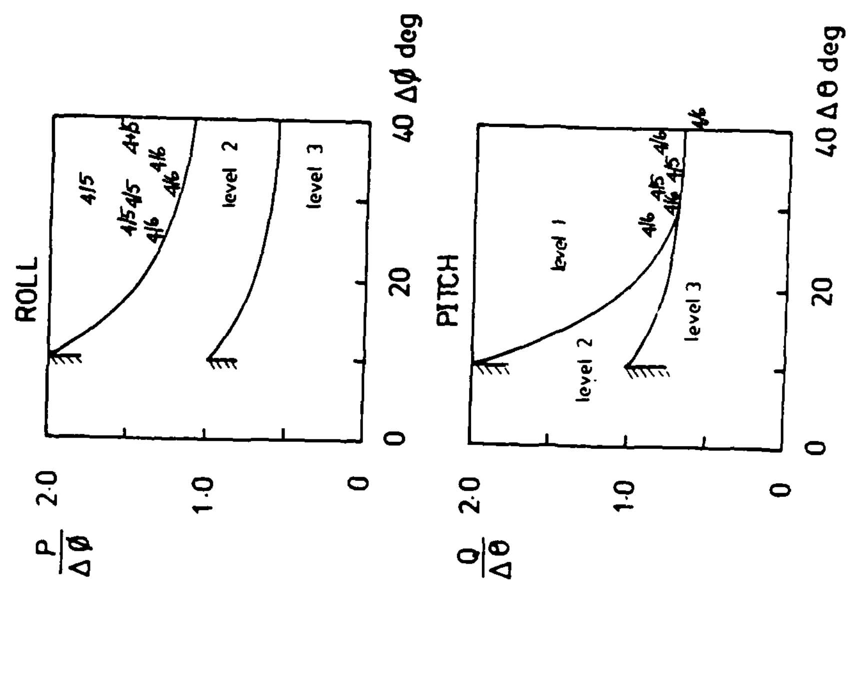


Fig 42 Lynx HQR's against proposed MIL-H-8501 criteria (Ref 5)

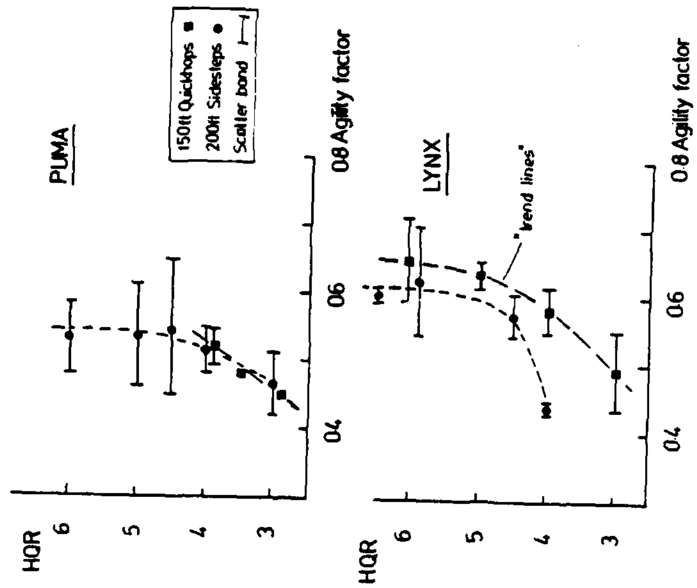


Fig 43 Variation of HQR with agility factor

REPORT DOCUMENTATION PAGE

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16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Helicopters. Handling qualities. Agility. Flight testing.

17. Abstract

There is work underway to revise the US MIL-H-8501 and the UK Def-Stan 00970 design requirements for the specification of handling qualities for military rotorcraft. This paper reports on current RAE research activities in support of the two programmes. The focus of this work has been an extensive series of flight trials to investigate handling and performance requirements for low level nap-of-earth operations. The paper introduces and discusses results of trials on two different aircraft in a small amplitude, high gain pitch tracking task, and for two discrete moderate amplitude manoeuvres.

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